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AN OVERVIEW OF THE EXTERNAL MAGNETIC FIELD WITH REGARD TO MAGNE--ETC(U)

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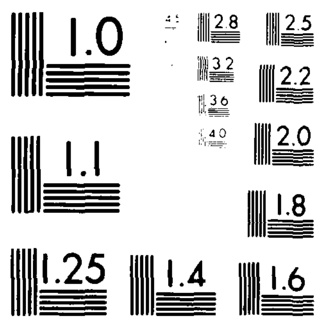

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PHOENIX CORPORATION
1700 OLD MEADOW ROAD, McLEAN, VIRGINIA 22102
(703) 790-1450 • TWX 710-833-0323

LEVEL II

An Overview of the External Magnetic
Field With Regard to Magnetic Surveys

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by

Robert D. Regan
Paul Rodriguez

Phoenix Corporation
1700 Old Meadow Road
McLean, Virginia 22102

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Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

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PREFACE

This report sponsored by the Earth Physics Program of the Office of Naval Research, is an attempt to bring together in a coherent manner, for those involved in magnetic surveys, the relevant aspects of the external geomagnetic field. Although there are several excellent introductory texts on geomagnetism that treat much of this subject (most notably, Sugiura and Heppner, 1968; and Knecht, 1972) it was thought that there was a need to condense and present this and other supportive material in a form that would be more applicable to the objectives of magnetic surveys, as there is considerable interest in correcting magnetic surveys for the effects of the external field. Such efforts must start with a sufficiently detailed understanding of the geomagnetic environment in which magnetic survey data are collected and particularly of the various external field sources. Hopefully this report will serve to provide such an understanding.

INTRODUCTION

Over the past few years there has been a definite trend in magnetic surveys, conducted for resource applications and defense purposes, toward more regional studies and at the same time toward more accurate and detailed local surveys. This is due in part to a change in philosophy of resource exploration in which the search for resources has taken on new dimensions. No longer are magnetic surveys conducted to map very obvious anomalies of the crustal field immediately indicative of resource deposits. The effort is rather directed toward broad scale studies focusing on more subtle secondary indicators of such deposits. Such an objective demands more accurate measurements of the crustal signal over sizable regions of the globe. Increased demands on surveys for defense purposes have arisen from the need to chart and map ever more subtle inflections of the magnetic field. To date, instrumental development both in terms of direct observations of the magnetic field and supportive measurements such as positional location have paced the requirements of such surveys. However the limiting factor is now the adequate extraction of the anomalous field signal from the total field measurement.

For basically the geomagnetic field can be, and is, naturally divided into three segments; internal, crustal or anomalous, and external. The internal field is that more stable primary field arising in the core region, essentially broad scale and containing only extremely low frequency temporal variations. Routinely monitored by magnetic observatory measurements, repeat stations, and satellite observations it is readily quantifiable by means of geomagnetic field models which serve as reference standards for the reduction and analysis of most magnetic observations.

Superimposed on this field is one of higher spatial frequency arising from the propensity of certain crustal materials and structures in the outer tens of kilometers of the earth to modify the internal field. This field is routinely mapped by ground, air, ship, and satellite measurements to aid in the search for minerals and fossil fuels and for pertinent defense applications.

The third component of the geomagnetic field is undoubtedly the most dynamic, complex and ubiquitous. Although we speak of the external field, we should perhaps more properly say external fields as this component of the geomagnetic field arises from many sources primarily due to the complex interaction between terrestrial and solar magnetic fields and other physical processes associated with the solar terrestrial environment. Although comprised of many sources, the external field can broadly be classified into ionospheric and nonionospheric sources.

The one factor that all areas of application and even theoretical studies of the geomagnetic field have in common is that any measurement of the geomagnetic field is a composite of these three components. This is the basis for the need for communication between investigators having primary interest in any one component of the field. They must have knowledge of the other components so these can be effectively removed and the signal of primary interest isolated. This complementary signal/noise relationship is also the underlying basis for the need for more effective understanding of the external fields in the areas of practical applications.

Perhaps nowhere is this more evident than in the mapping of the anomalous field. Through the concerted efforts of several dedicated geomagneticians over the past few years it is now possible to routinely and accurately remove the effect of the internal field from total field measurements through subtraction of a suitable geomagnetic reference field. However the same is not true for the external field. Indeed we are just entering an era in which the need to correct for external (or temporal) variations has become blatantly apparent. However the external field is quite different from the internal and anomalous field and certainly, as mentioned, more complex. In order to effectively remove such variations from survey data, their sources and morphologies must be understood. This is the intent of this report. We first discuss, in detail, the geomagnetic environment of the earth and then examine individually the various external fields. Finally the magnetic activity indices, the quantitative indicators of the state of the external field are discussed.

MAGNETIC ENVIRONMENT OF THE EARTH

Observations of the earth's magnetic field for the last two or more centuries have shown that the geomagnetic field is essentially a steady-state field that does however exhibit long and short term variations. The long term variations have time scales of hundreds of centuries and affect the total strength and direction of the magnetic field, such as a reversal of the field polarity. These long term variations are quasi-periodic and are associated with the dynamics of the magnetic dynamo internal to the earth. For practical proposes, these variations have such long time scales that we can assume, especially for magnetic survey purposes, that a steady state configuration exists for the earth's internal magnetic field. This configuration is predominantly that of a dipole with a magnetic moment of about 8×10^{25} Gauss cm^{-3}, approximately parallel to the earth's rotation axis. It is now known, however, that the geometry of the earth's magnetic field is more complex than a simple dipole. If there exist measurements of the internal field at many places on the surface of the earth, then a spherical harmonic series can be fit to them to produce a mathematical representation of the data. Similar to fitting a curve to a series of points, a spherical harmonic function is the fitting of a surface to a number of points on a sphere. This representation is termed a geomagnetic field model and is a function of latitude ϕ, longitude θ, altitude (or geocentric distance) r, and time t.

The spherical harmonic representation of the potential of the field is

$$V = a \sum_{n=1}^{\infty} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^{n} (g_n^m \cos m\phi + h_n^m \sin m\phi)\ P_n^m(\theta) \tag{1}$$

where

V = magnetic potential

a = mean radius of the earth

m,n = order, degree; and

$P_m^n(\theta)$ = Schmidt's quasi normalized spherical functions

The set of Gauss coefficients (g,h) are determined by a least squares fit.

Some nomenclature for the description of the field must be introduced before an accurate picture of the derived internal field can be presented. Figure 1 shows the relationships between the various field elements. F is the total field vector. The angle it makes with the horizontal is the inclination (positive down), its horizontal component is H, and its angle with geographic north is called the declination (positive clockwise). The geographic North, East, and Vertical (positive downward) elements are termed the x, y, and z components, respectively. These various components of the geomagnetic field are obtained from the potential expansion (1) by taking the appropriate derivatives. Figures 2, 3, and 4 show the resultant calculation of F, I, and D. From Figure 2, it can be seen that the intensity of the field varies from 24,000 gammas (basic unit of magnetic intensity; 1 gamma = 10^{-5} Gauss) to approximately 60,000 gammas. We have already noted the long term variation of the field that has been detected through historical observations. The time parameter is introduced in the spherical harmonic analysis by expanding the Gauss coefficients in a finite Taylor serves about some mean time of the data set. The present secular variation computed in this manner is shown in Figure 5.

Although, as the figures relate, the field is quite complex, conceptually, it should be thought of as a dipole with the attendant variation of inclination with latitude. If the earth were in a field free space then the view of the magnetic field from a distant vantage point would be just this simple (Figure 6). However, the earth's magnetic field is greatly influenced by electromagnetic radiation, charged particles, and magnetic fields emitted by the sun. The latter two elements gives rise to the classic shape of the earth's magnetic field called the magnetosphere.

Magnetosphere

The near dipole geometry that is detected for the magnetic field near the surface of the earth is modified at large distances from the earth by the interaction between the solar wind (a hot, completely ionized gas, or plasma, composed mainly of electrons and protons) and the geomagnetic field. In this interaction, three current systems are established that distort the dipole geometry into the magnetosphere geometry shown in Figure 7. Since the

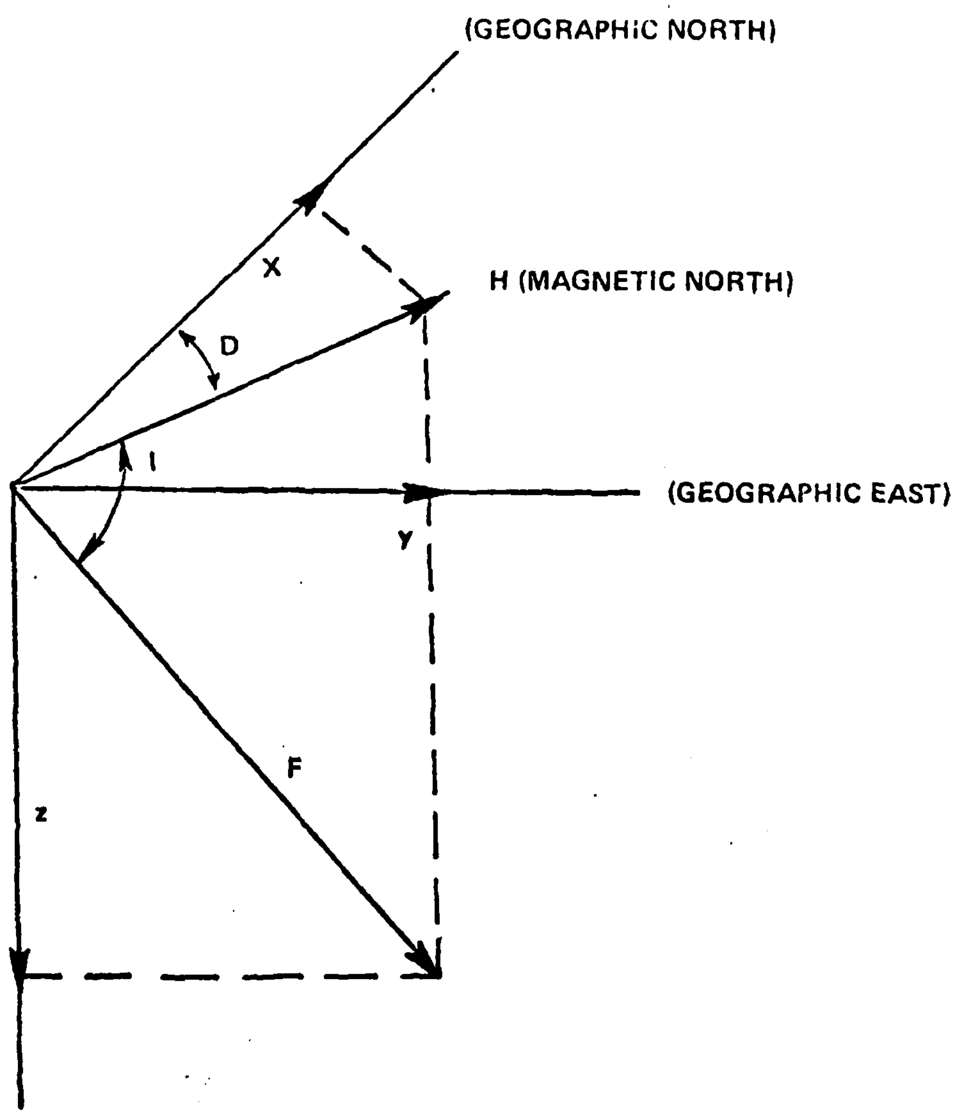

Figure 1. Relationship of magnetic field components

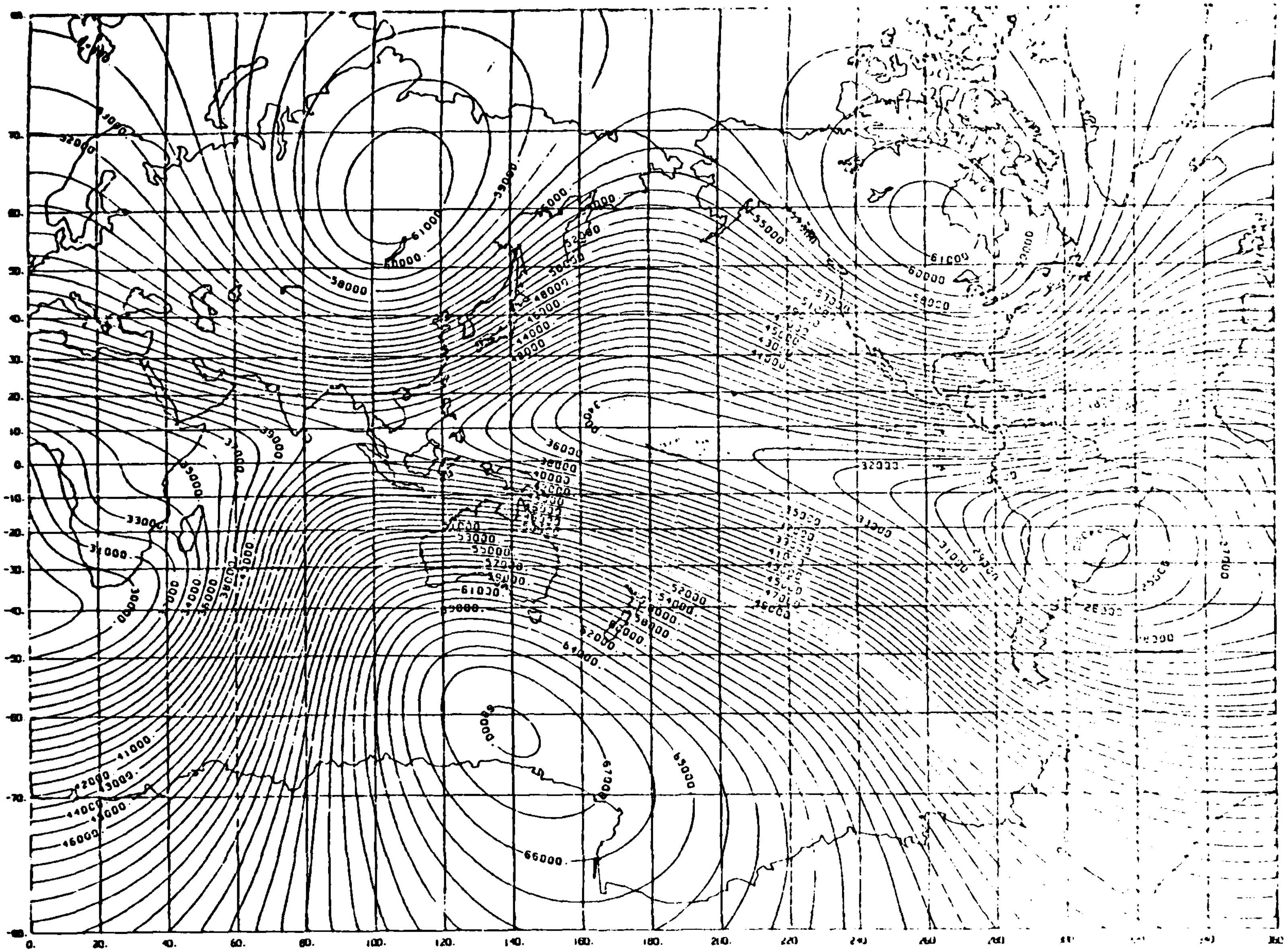

Figure 2. Map of total intensity (F) for 1977.0 contour internal is 1000 gammas.

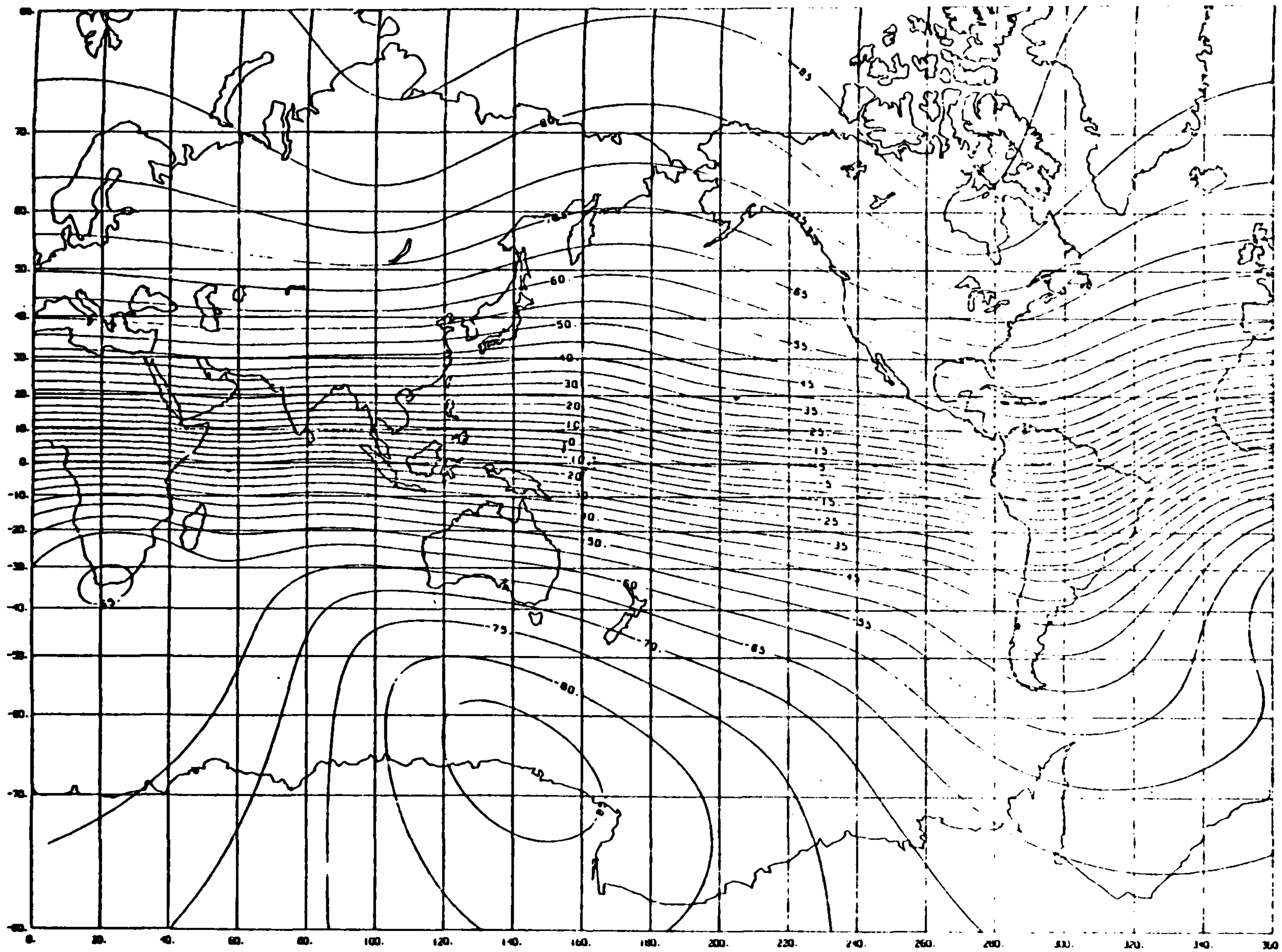

Figure 3. Map of inclination (I) for 1977.0 contour internal is 5 degrees

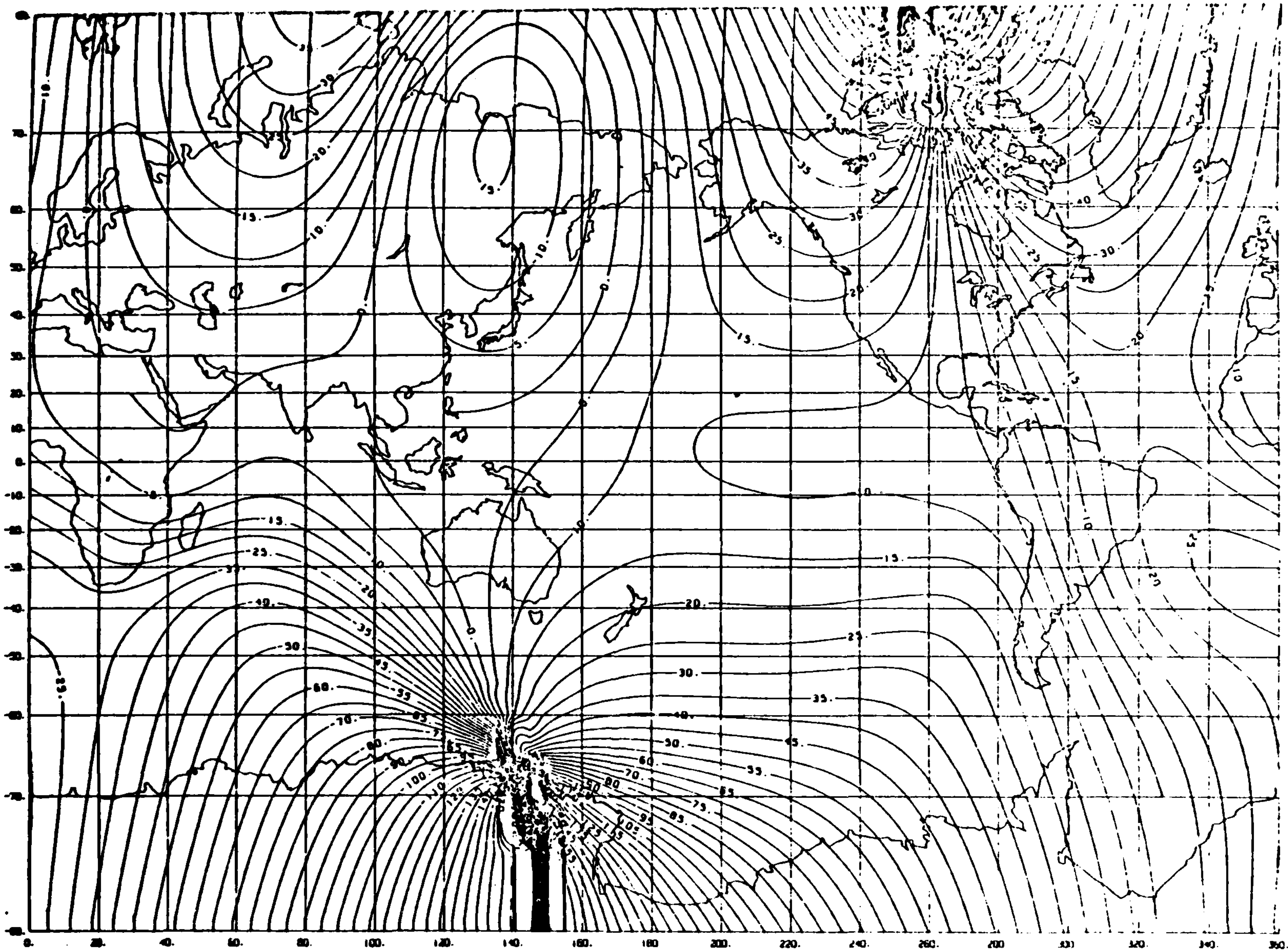

Figure 4. Map of declination (D) for 1977.0 contour internal is 5 degrees.

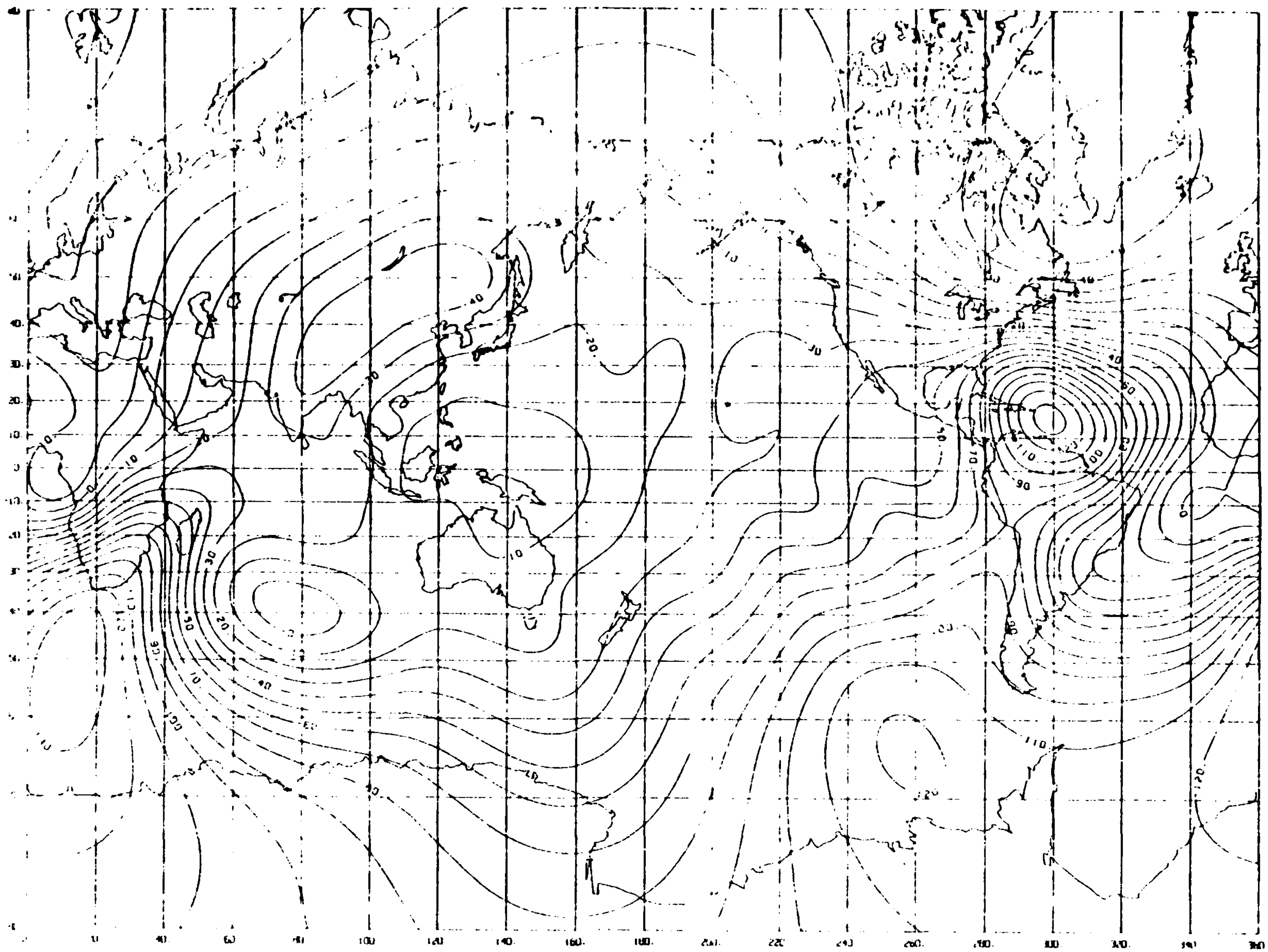

Figure 5. Map of Total Field Intensity Secular Variation ($\dot{F}$) for 1977.0
Contour Interval is 10 Gammas/Year.

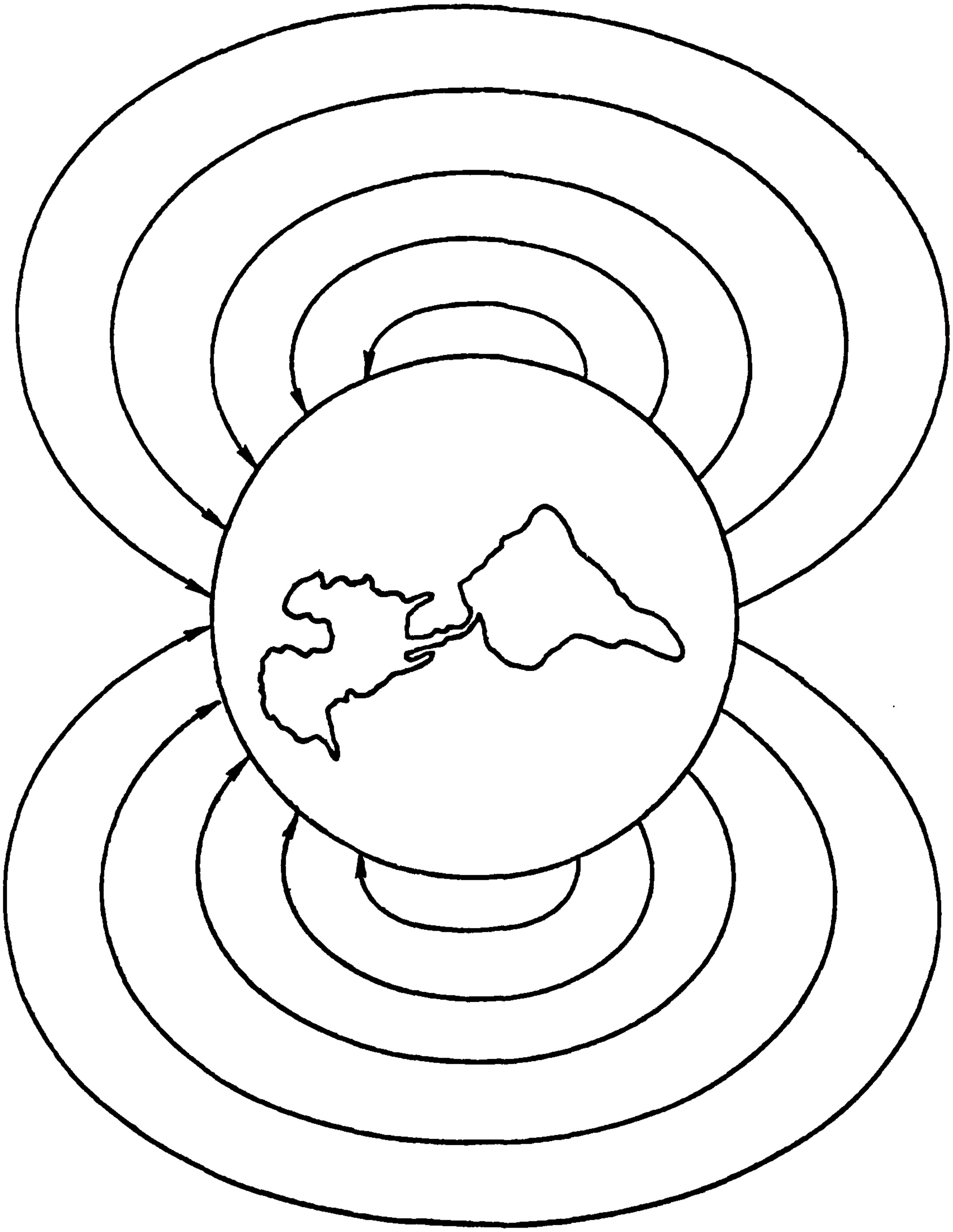

Figure 6. Schematic view of dipole field showing lines of force.

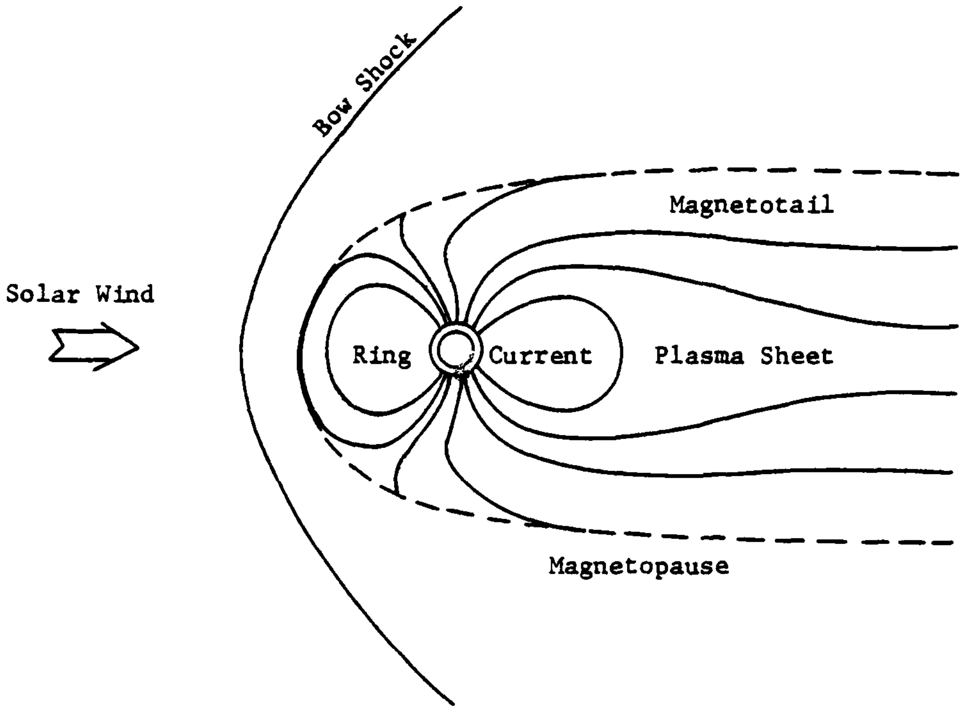

Figure 7. The magnetosphere of the earth, viewed from the plane of the ecliptic.

solar wind flows away from the sun at supersonic speeds, a shock wave is first formed around the obstacle of the earth's magnetic field, somewhat similar to the bow wave that results when a boat moves through water. The entire process results in the development of three major magnetospheric current systems that affect magnetic survey data to varying degrees. Inward of the bow shock the first current system, called the magnetopause, is formed. The magnetopause is the actual boundary between the solar wind and the earth's magnetic field. The pressure of the solar wind compresses the sunward side of the earth's magnetic field and stretches the antisunward side into a long magnetotail. The exact nature of the interaction is not well understood, but it apparently involves a viscous interaction between solar wind and magnetospheric plasmas. In terms of earth radii ($1R_e \approx 6370$ km), the sunward position of the magnetopause occurs at about 10 R_e and the magnetotail is thought to stretch in the antisolar direction several hundred earth radii. The current system on the magnetopause surface provides the magnetic field perturbation that produces the nondipolar geometry of the distant geomagnetic field. The field lines emanating from the north and south magnetic poles of the earth are stretched back to form two lobes of oppositely directed magnetic field lines in the magnetotail. At the boundary between these two lobes the magnetic field must reverse sign and therefore a current system must be established there. This current system is called the plasma sheet and forms the second basic current system of the magnetosphere. At distances closer to the earth the magnetopause and plasma sheet currents are less effective and the field lines begin to assume a more dipolar geometry. However, the solar wind interaction can still be felt through the third major current system, called the ring current. The ring current is generated by protons and electrons trapped in the nearly dipolar magnetic field below about 7-9 R_e. These trapped particles drift longitudinally in opposite directions due to the radial gradient in magnetic field intensity and produce a net westward current around the earth. In Figure 8 we show a schematic diagram of the location and flow directions of these current systems which are discussed in more detail in the following sections. These current systems produce magnetic field perturbations that are additional to the main geomagnetic field that can be detected on the ground by magnetic field observatories and contribute to the results of magnetic surveys. Generally, the perturbations are manifested in two distinct ways, as a steady state change and/or as an impulsive variation.

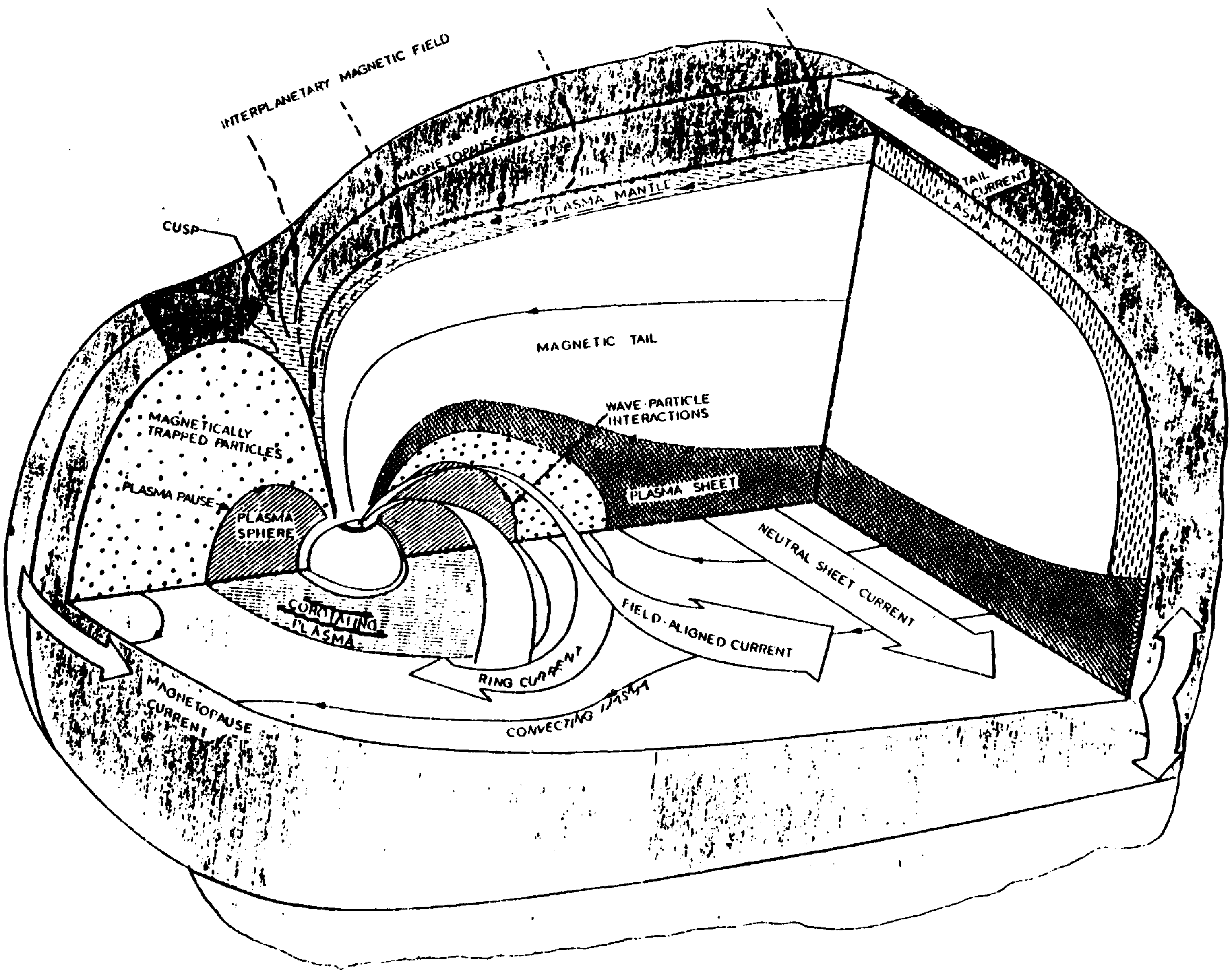

Figure 8. Expanded view of the magnetosphere showing magnetospheric regions and currents.

Magnetopause Current

The magnetopause current is generated by an interaction between solar wind and magnetospheric plasmas that appears to involve a merging of interplanetary magnetic field lines from the solar wind with geomagnetic field lines. The merging results in a transfer of magnetic flux from the sunward side into the magnetotail where the associated magnetic field energy is stored. Variations in solar wind pressure or magnetic field can cause oscillations of the magnetopause merging rate which results in various wave motions being propagated throughout the magnetosphere. These wave motions can be very coherent oscillations of the magnetic field with periods of seconds to minutes, or impulsive variations with no distinct periodicity. The amplitudes of these waves, called micropulsations, are on the order of several gammas.

Plasma Sheet Current

Although the plasma sheet current is enormous in extent, its large distance from the earth reduces its steady state perturbation on the near earth magnetic field. However, large impulsive perturbations occurring in the polar regions are apparently connected with large scale disruptions of the plasma sheet current. The cause of these disruptions is not well understood but seems to result from an instability in the magnetotail configuration. The magnetotail instability releases much of the magnetic field energy stored in the form of magnetic flux derived from the merging process occurring at the magnetopause. The disrupted plasma sheet current finds its way into the polar regions of the geomagnetic field and produces the well known signature of magnetic substorms: magnetic bays (decreases in the horizontal magnetic field) with magnitudes on the order of 100 gammas. On occasion, a strong interplanetary shock or sudden favorable orientation of the interplanetary magnetic field can trigger a magnetotail instability to produce magnetic substorms. Since interplanetary shocks are often produced by solar flares, magnetic substorms are correlated with the solar flares. It was this correlation which historically led to the present understanding of solar wind-magnetosphere interactions.

Ring Current

The ring current is a more steady-state current system than either the magnetopause or plasma sheet current, but during magnetic storms, particles from the plasma sheet are injected into the ring current to produce additional magnetic field perturbations which are detected at low latitudes on the earth's surface. On such occasions the ring current generates a perturbation field opposite to the main geomagnetic field and thus causes a depression of the field observed on the surface. The perturbation is on the order of 100 gammas.

Ionosphere

In addition, components of emitted solar electromagnetic radiation give rise to a current system in the 90 to 130 km altitude range which because of its proximity to the ground has a profound effect on ground and magnetic survey measurements.

An examination of a graph of the electromagnetic spectrum reveals that the atmospheric absorption at wavelengths below the visible is almost complete. Although this has precluded the use of this region in classical remote sensing studies, the atmospheric absorption of the X and ultraviolet radiation gives rise to the ionospheric current system. The X rays ionize the atmosphere predominantly in the region from 90 to 130 km creating an ionosphere while the ultraviolet rays provide differential heating over this density stratified medium resulting in atmospheric turbulence. The resulting motion of the charged particles in the presence of the earth's magnetic field gives rise to a current system which produces a magnetic field which is one of the most predominant external sources. A simplified version of this current called the Sq (for solar-quiet) current is shown schematically in Figure 9.

However the manner in which the current is produced is complex because in an ionized gas in the presence of a magnetic field (as is the case of the ionosphere) the electric current does not necessarily flow in the direction of the electric field.

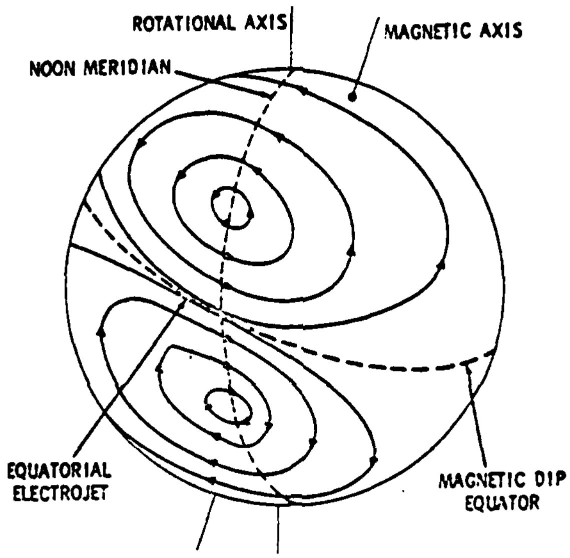

Figure 9. Sq current system schematically represented. Currents flow in the direction of arrows (Sugiura and Heppner, 1968).

In the case of an infinite ionized layer when the electric field is parallel to the magnetic field then the current is parallel to both. When the electric field is perpendicular to the magnetic field then there is a current parallel to the electric field (Pederson current) and one at right angles to both (Hall current) (N.B., the names Pederson and Hall properly apply to the conductivities in the equations for these current but for our purposes we have applied the names to the currents as well). In the case of the ionosphere, which is of a finite thickness, an additional electric field is imposed due to the natural polarization of the finite ionized gas. This results in an increase in current in the primary electric field direction due to the original Pederson current and an induced Hall current resulting from the polarization field and the magnetic field. These currents are combined to be called Cowling currents.

Knowing the conductivity distribution in the ionosphere it is apparent that the magnetic field observed requires winds of several hundreds of km/hr. These are a result of the solar heating as well as gravitational attraction of both the sun and moon. Such heating and gravitational attraction causes much more complicated tidal features in the stratified atmosphere than are observed in ocean tides.

External Fields

This complex system of currents then gives rise to the magnetic variations that are termed external field variations. As we have noted these four current systems are the major current systems that produce the most notable effects in magnetic survey data. In addition there are minor current systems such as field aligned currents, i.e., current directed along the geomagnetic field lines caused by the motion of trapped particles, which complete the electrical circuit between ionospheric and magnetospheric currents as well as sporadic currents in the auroral and polar regions connected with the infusion of charged particles and release of magnegic flux energy from the tail region. In general the magnetic environment of the earth consists of the steady internal field modulated by its interaction with the solar effects and the resultant current systems operating in primarily a steady state condition.

In addition the long term solar cycle (evidenced in Figure 10) gives rise to long term modulations and a periodic release of both corpuscular and electromagnetic radiation from solar sources causes additional sporadic modifications of the magnetospheric morphology and current systems.

In general it is difficult to separate out from ground based observations the purely external part of the geomagnetic field. Nevertheless the spherical harmonic expansion utilized to model the internal field can be modified to include the external field and the external coefficients determined from repeated analysis of magnetic observatory data. Basically the expansion for the potential (1) utilized in modeling the internal field is modified to include the external field. In a general form this is

$$V = a \sum_{n=1}^{\infty} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^{n} I_n^m P_n^m(\theta,\phi) + \left(\frac{r}{a}\right)^n \sum_{m=0}^{n} E_n^m P_n^m(\theta,\phi) \qquad (2)$$

where

I_n^m and E_n^m are the internal and external coefficient respectively.

Also, many of the external fields as well as the entire geomagnetic field are best viewed in a geomagnetic reference system rather than a geographic or geodetic one. Figure 11 shows these two reference systems. Basically the geomagnetic reference system is a spherical coordinate system with origin at the earth's center and axis parallel to the geomagnetic dipole. Latitude and longitude are termed geomagnetic latitude and longitude and geomagnetic local time is defined analagous to conventional local time. For example geomagnetic local noon is when the sun is in the meridian plane defined by the observers location and the geomagnetic poles. Chapman and Bartels (1940, p. 645) give equations for converting geographic to geomagnetic coordinates.

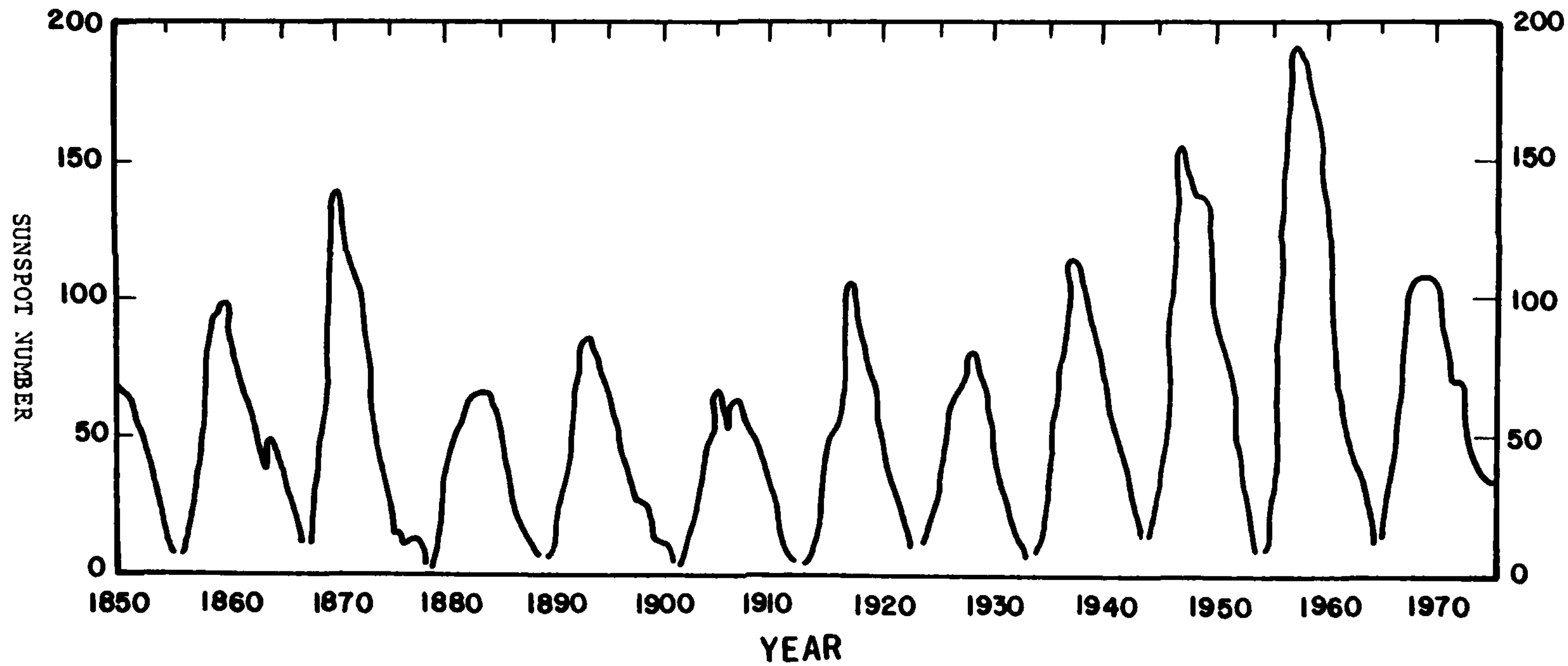

Figure 10. The yearly number of sunspots for the past one hundred twenty-five years (Lanzerotti, pers., comm.).

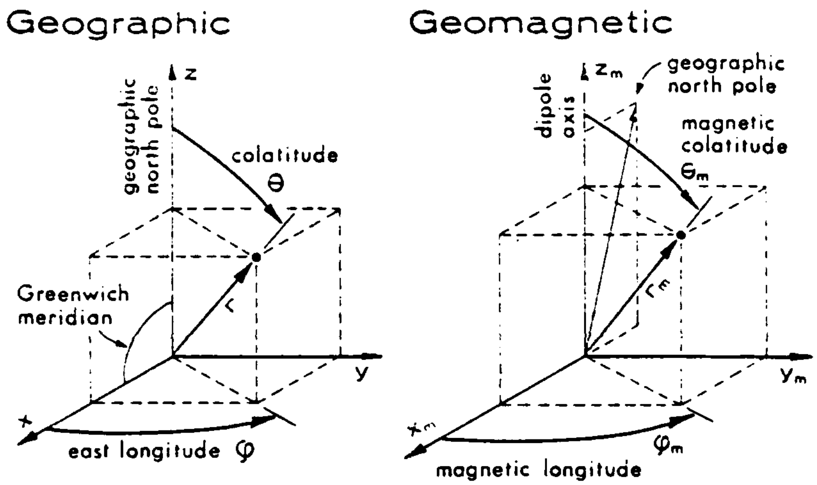

Figure 11. Geographic and geomagnetic coordinate systems (Knecht, 1972)

EXTERNAL MAGNETIC FIELD

The external magnetic field as observed at (or near) the surface of the earth is the combined effect of the magnetic fields resultant from the various current systems at any single time. The external field signal however is further complicated by the fact that these time varying magnetic fields induce earth currents whose configuration and intensity vary depending upon the internal conductivity structure. Thus the observed external field has a component due to the primary source current as well as one due to the induced secondary current. In the case of the ionospheric currents the induced component observed at the earth's surface constitutes approximately 30% of the signals. For the purposes of the report the induced fields will not be considered and the external fields discussed will be those due to the primary sources.

Having considered the magnetic environment of the earth and the primary external field sources it is perhaps best to present the external fields according to their observed phenomena. In doing so we will consider the source structure, the observed signal and touch on secondary modifications of the signal. The fields to be discussed are divided into quiet (or more steady state) and disturbed variations.

Quiet Variations

If recordings of the geomagnetic field intensity as a function of time (magnetograms) from various magnetic observatories are examined, a general indication of the variability of the external field can be obtained. For, as the observatory remains stationary relative to the internal and anomalous fields then the variations observed are due to the external field. Recordings reveal that this field contains components that for the most part are predictable and steady as well as highly unpredictable aperiodic fluctuations. Although the specific character of a magnetogram is dependent upon the observatory's geographic location (mostly a latitude dependence) the general separation of the external field into stable (quiet) and disturbed (aperiodic) components is globally valid.

Ionospheric Sources

The magnetic field observed at any location on the earth goes through a repeatable daily variation of several tens of gammas depending upon the station location. An example of some typical magnetograms showing this variation is presented in Figure 12. This effect is caused by the main ionospheric current and is called the Sq effect, with Sq symbolizing solar-quiet. The physics developed for the current generation is consistent with the observation that the observed signal reaches its maximum at local noon and is at a minimum or absent in the nighttime. The variation with latitude is attributable, among other things, to the variation of atmospheric conductivity with latitude as conductivity is the most important parameter and is controlled by the strength of the internal field which, as has been noted, varies with latitude.

Knowing the general pattern of the ionospheric level winds and associated conductivities a detailed model of the Sq current system can be computed. Such a model is shown in Figure 13. As can be seen the current system is more complex than the general schematic shown in Figure 9 and is highly variable depending upon season. This is not surprising owing to the fact that solar radiation is the primary cause of the current system. The pattern consists of one current system in each hemisphere with foci at approximately 30° latitude. It remains stationary with respect to the sun with the foci traversing lines of equal geomagnetic dip. The currents move counter clockwise in the northern hemisphere and clockwise in the southern hemisphere with the summer hemisphere current being more intense. The current is also dependent on the solar cycle due primarily to the fact that the conductivity increases by approximately 50 percent during times of solar maximum.

In addition to the modeling of the current system the Sq effect can also be mathematically modeled. Isolating the Sq effect from 60 observatories over selected time periods, Sugiura and Hagan (1967) have developed a spherical harmonic expansion model. The results of their model (Figure 14) show that the observed field is more complicated than shown from individual observatory records. This is undoubtedly due to the sparse distribution of observatories. The signals become quite complex in higher latitudes where there is undoubtedly some coupling existant between the Sq current and magnetospheric sources. The model however can be utilized to study in detail what affect the primary Sq magnetic field will have on magnetic survey data.

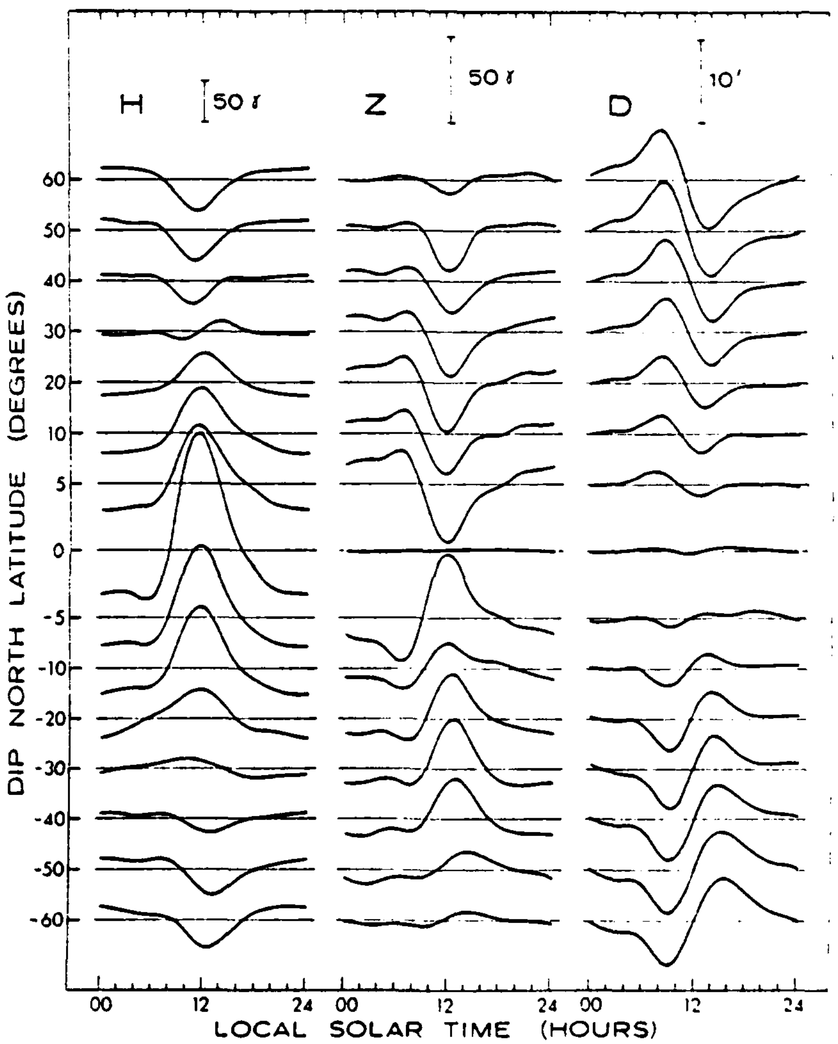

Figure 12. Worldwide average of the solar quiet daily variation for the months March, April, September, and October, 1958 (Solar Maximum) [combined and redrawn after Matsushita, 1967], (Knecht, 1972).

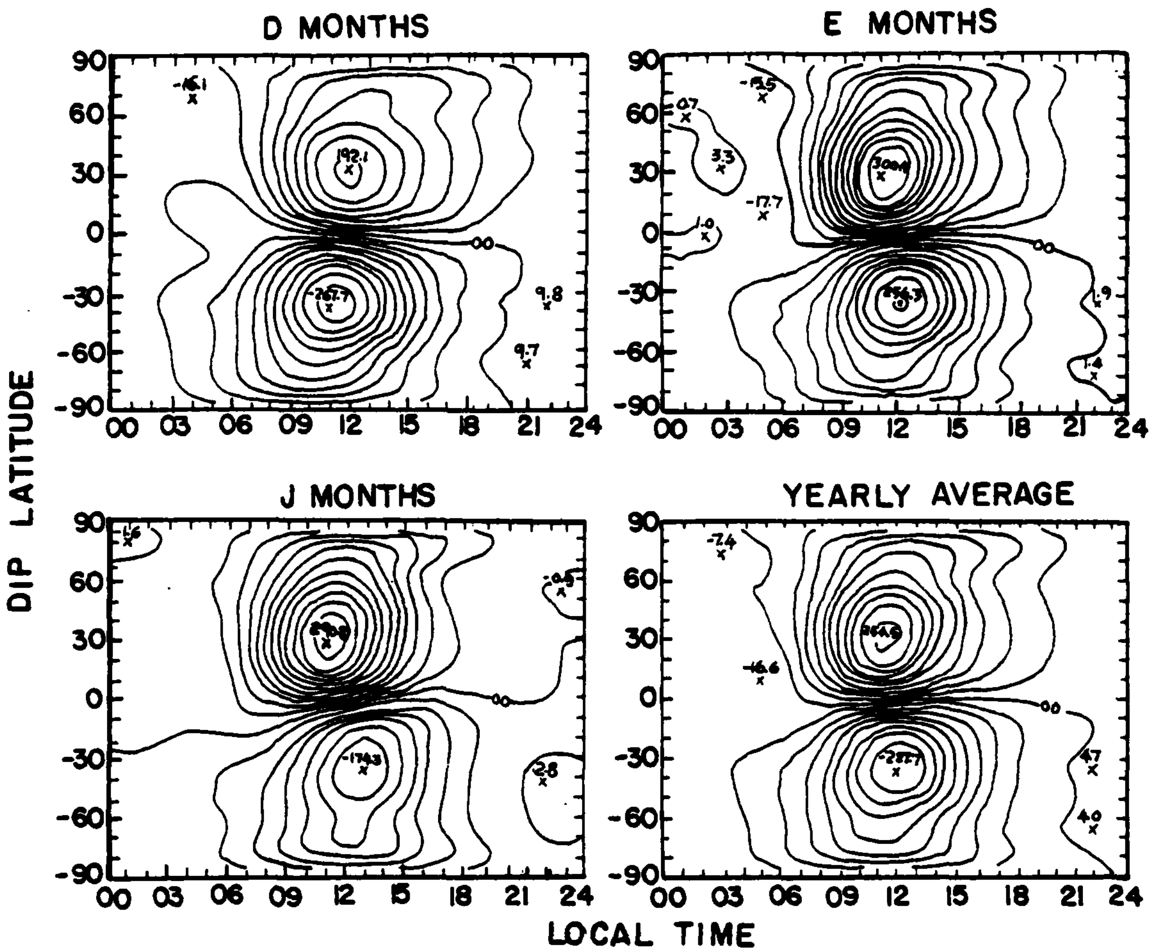

Figure 13. Computer-plotted external Sq current systems for December solstitial, equinoctial, and June solstitial seasons and the yearly average during the IGY(1958) when the current intensity at the midnight is zero. The current intensity between two consecutive lines is 25 x 10^3 amp, and the numbers near the cross marks indicate the total current intensities of vortices in units of 10^3 amp (Matsushita, 1969).

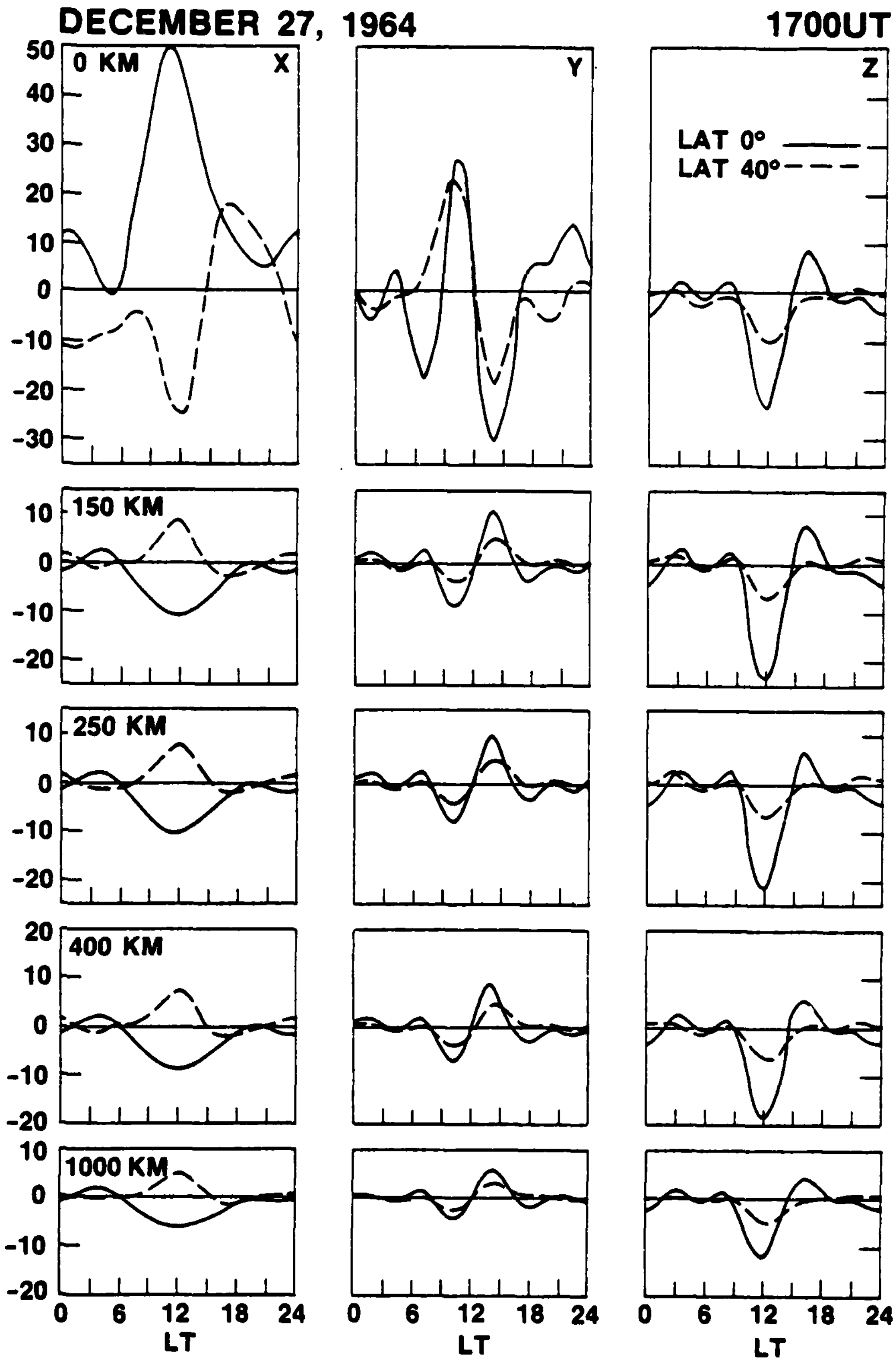

Figure 14. Component magnetic fields due to the Sq current system of December 27, 1964 at latitudes 0° and 40° north as a function of altitude.

Another driving force of the atmospheric circulation is the gravitational attraction of the moon. Accordingly there is also a secondary component, termed the L effect (for Lunar), to the Sq field. Although the resultant field is quite small and difficult to isolate, because of the similarity between the length of the solar and lunar days a current system can be fit to the data. This current system is shown in Figure 15. Although more complex and dependent on lunar phase as well as season, this signal is not of great concern to magnetic surveys.

The extreme amplification of the Sq effect near the geomagnetic equator is apparent in the low latitude magnetograms shown in Figure 12. This is due to a highly concentrated eastward current system, termed the equatorial electrojet, flowing within a few degrees of the geomagnetic equator. Cain and Sweeney (1973) have mapped out the trace of the electrojet from satellite data as shown in Figure 16. The current is a result of an increase in Cowling conductivity near the equator. At the equator the geomagnetic field is horizontal and northward with the naturally polarized ionospheric field at right angles. As mentioned earlier this sets up an ideal situation for a Cowling current. Thus this region is one to which particular attention should be paid in terms of correcting magnetic fields for Sq effects.

Magnetospheric Sources

To date any daily or regular periodic variations due to the magnetospheric current systems have not been detected. Although the day side and night side difference in the configuration of these currents and in general other assymetries in the current systems should produce variations, they are undoubtedly quite small and of the order of one or two gammas.

However the general apparent strength of the entire field can vary over periods of several days due to variation in solar pressure and geomagnetic flux. This effect however is aperiodic and discussed in the next section.

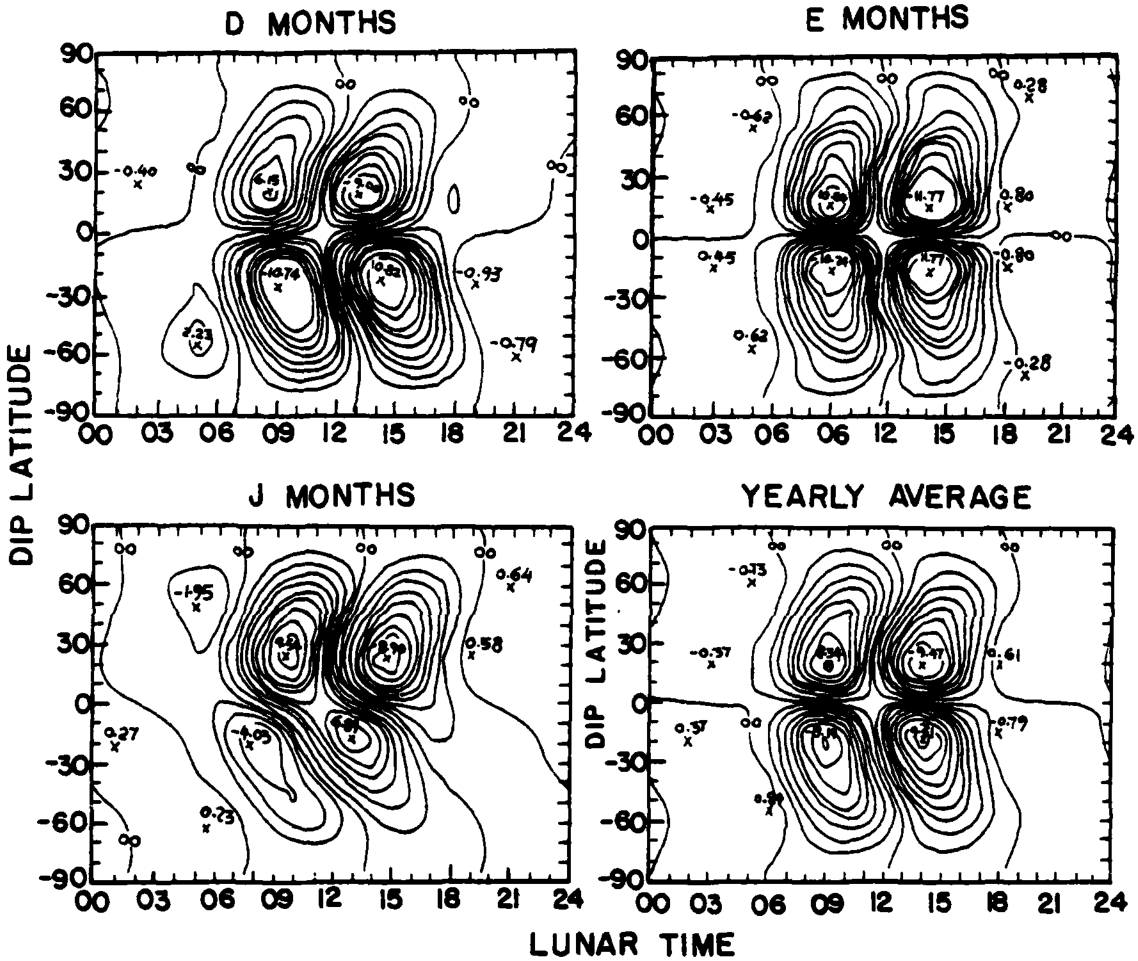

Figure 15. Estimated L current for a new moon (or luni-solar current system) during three seasons and the yearly average (moderate sunspot period). The current intensity between two consecutive lines is 10^3 amp. (Matsushita, 1969)

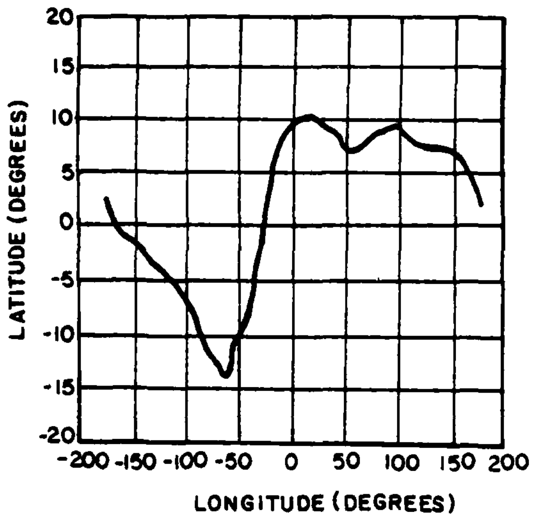

Figure 16. Average latitude of electrojet centers observed by POGO. (Cain and Sweeney, 1973).

Disturbed Variations

The complexity of the magnetospheric structure, current system and the variation in output of solar radiation, charged particles, and magnetic field (both direction and intensity) all indicate the external field is highly variable. For the most part, the variations range from low level high frequency micropulsations through single isolated disturbances in the polar regions to planetary wide intense magnetic variations lasting several days termed magnetic storms. However this melange of disturbances can be classified with particular disturbances and sources being isolated.

The ultimate cause of the disturbed variations is the direct interaction of solar energy and magnetic field lines with the magnetosphere as well as the resultant growth and decay of the primary magnetospheric currents and changes of energy balance within the magnetosphere (particularly release of energy from the magnetotail). Perhaps nowhere is the entire concept of the disturbance field more evident nor all of these factors more dramatically involved than in geomagnetic storms.

Such events are global in nature affecting all magnetic measurements as well as making their existence known in the visible aurora and through sporadic effects on communication systems. The morphology of a typical storm is well known but only recently has the physics behind the cause become completely understood. A typical storm magnetogram is shown in Figure 17. The storm usually begins with a sharp sudden increase in the field followed by several hours during which the field remains many tens of gammas above the pre-storm level. This phase, termed the initial phase, is followed by the main phase in which the magnetic field is drastically lowered to hundreds of gammas below the pre-storm value. The recovery phase lasting several days is that phase of the storm during which the field returns to its normal condition.

The ultimate cause of the storm is a solar plasma cloud, generated from an intense solar flare, which produces a shock wave in the interplanetary plasma. The storm begins when the shock wave and plasma cloud interact with the magnetosphere. The initial phase of the storm is due to the sudden compression of the magnetosphere caused by the shock wave. The compressive effect is also augmented by increased boundary or magnetopause currents. The main phase of the storm is due to the ring current that becomes enhanced as a result

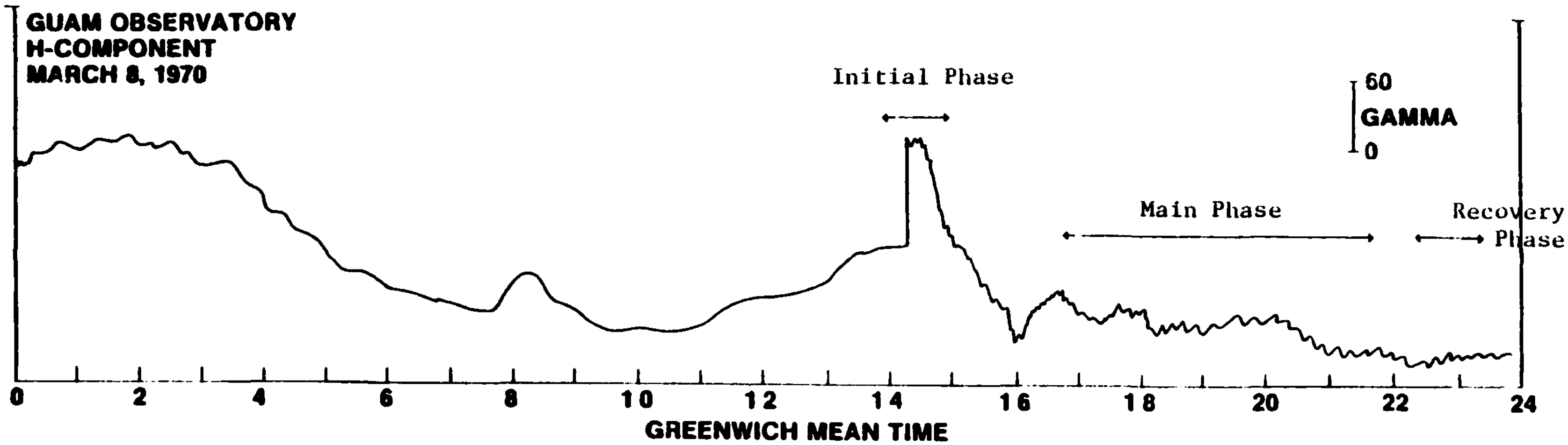

Figure 17. Guam geomagnetic observatory magnetogram for magnetic storm of March 8, 1970.

of complex release of particles within the magnetosphere. The complex processes releasing energetic particles are called magnetospheric substorms and can and do occur separately from a storm. Basically when they occur close together their combined effect produces the main phase of the storm. These substorms resulting from magnetotail instabilities cause energetic protons to be injected into the ring current region and the resultant current reduces the global (especially lower latitude) magnetic field. The main phase also contains components of a polar magnetic substorm or the magnetic manifestation of the magnetospheric substorms in the polar/auroral region as a result of intense ionospheric and field aligned currents.

As noted before, the geomagnetic storm is the most intense and dramatic feature of the disturbed external field and is related to other disturbed variations in that it is a composite of magnetospheric substorms which are also manifest as aurora and related magnetic and ionospheric disturbances. Except for the global effects of the magnetic storm other disturbed variations are best studied by considering various geomagnetic regions of the globe. Because of the complexity of the auroral region it is worth concentrating first on disturbance fields in this region.

Auroral Zone Disturbances

The auroral zone is that area surrounding the poles in which the aurora occur. While highly variable in exact location (e.g., see Figure 18) depending upon solar activity, season etc. it can generally be ascribed to that region between 63° and 72° geomagnetic latitude. An examination of Figure 8 reveals that this is the region where the field lines from the magnetosphere connect into the ionospheric (actually the projection of the boundary between the inner and outer magnetosphere). This field line arrangement permits solar particles and interplanetary magnetic field line entry and as such is a locale for the most complex of geomagnetic phenomena. Indeed all of the sources and effects are not yet completely understood.

The categorization or discussion of the various external fields in this region is made difficult by the lack of such a complete understanding of the physics of the region, as well as confusing and often contradicting terminology and nomenclature in the literature, and inconsistency or confusion resulting

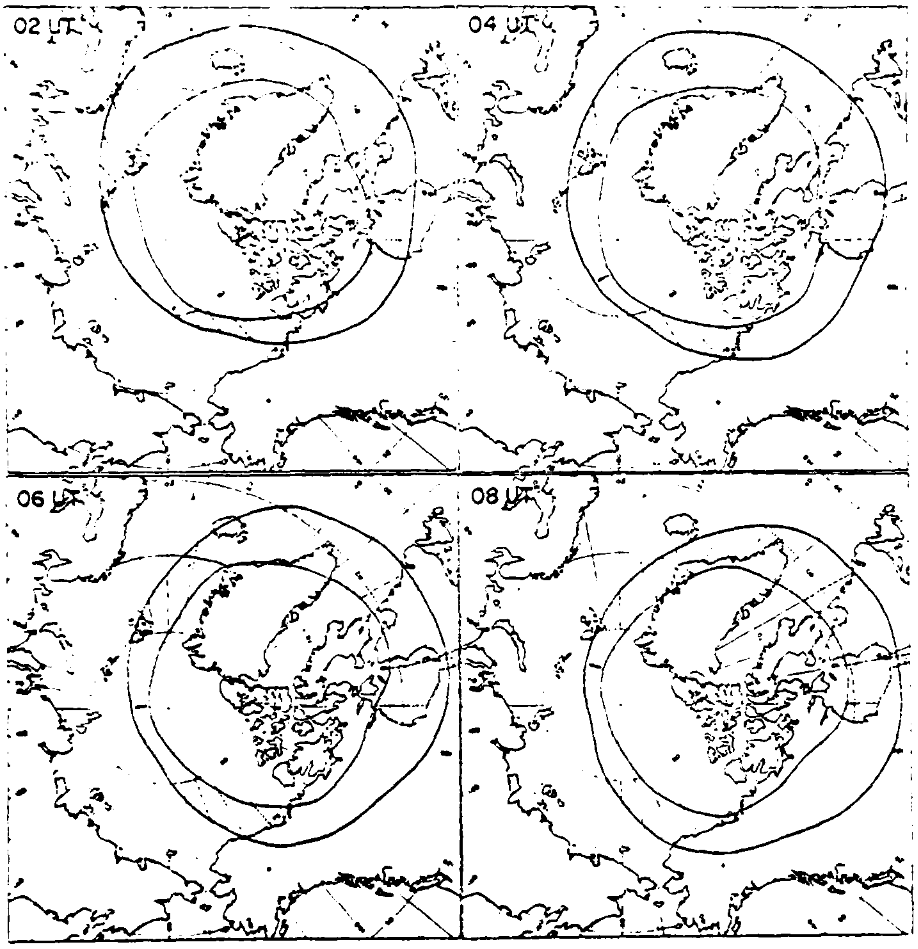

Figure 18. Approximate location of the auroral oval in the Northern Hemisphere at different UT hours (Akasofu, 1968).

presenting sources as mathematical models, conceptual current systems, or equivalent current systems. However, there are three main well defined current systems that should be considered in any discussion of this region. These are denoted as S_q^P, DP1, and DP2.

There has been observed in the auroral regions a quiet daily variation (difficult to extract as the field is disturbed 80-90% of the time) that has been likened to the Sq effect. Figure 19 shows an example from the Baker Lake magnetic observatory. The effect and current system have been termed S_q^P. The current system consists of an inward field-aligned current from the morning side of the magnetopause to the morning half of the auroral oval and an outward field aligned current from the afternoon half of the oval to the afternoon side of the magnetopause, together with associated ionospheric currents. One of the connecting currents in the ionosphere is undoubtedly the convection electrojet occuring in the auroral region. A schematic view of this current system is shown in Figure 20. The generation of these current systems is a complex process involving energy and currents in the tail region of the magnetosphere. The currents are also highly amplified during increased solar activity which, as noted, is visually evidenced in the aurora.

The visible aurora are due to electrons, emitted by the sun, streaming down the geomagnetic field lines (following a helical path of decreasing radius) and interacting with atmospheric constituents. The electrons upon reaching a critical altitude then traverse back out along the field lines. However at the end of their path the small component of horizontal motion is sufficient to leave a net horizontal current. Consequently there is a strong current in the ionosphere during intense auroral activity. This current is directed eastward in the late evening sector and westward in the morning sector. The exact location and configuration of the current system and whether or not it is closed over the polar cap or through field aligned currents is a subject of ongoing investigation, although from the previous discussion it appears to be the latter case. Also, no increase in Sq current flow has been noted during magnetic storms suggesting that the auroral zone currents diverge into the magnetosphere through field aligned currents rather than closing through the ionosphere. By analogy with jet stream winds, and in a similar derivation as the equatorial electrojet, this system is termed the auroral electrojet. The signal associated with the electrojet as recorded on several magnetograms is shown in Figure 21. This signal is termed a magnetic bay (also known as polar elementary storm) and is most

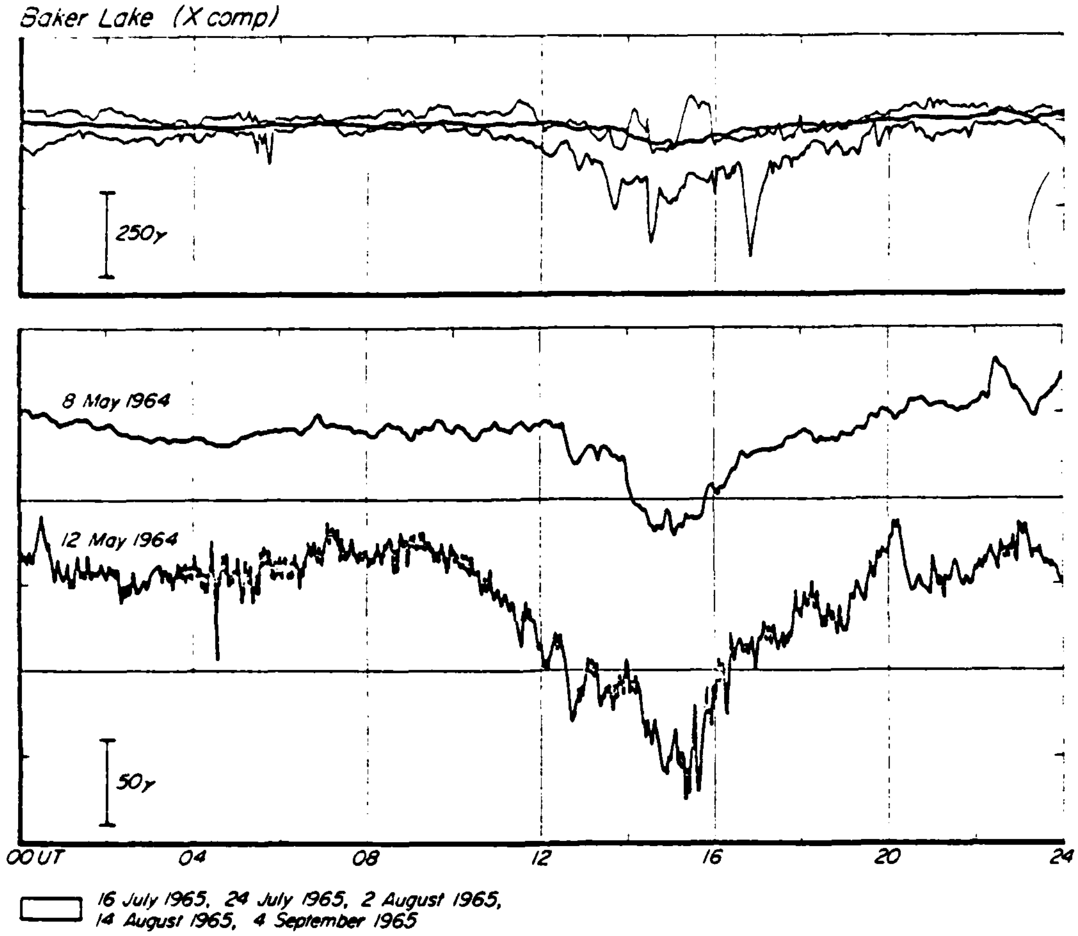

Figure 19. S_q^p variation at a polar cap station. Upper and lower envelopes of the superimposed magnetic records (the X component) from Baker Lake on several moderately disturbed days, together with the same component on 1964, May 8, one of the most quiet days during the IQSY. In the lower part, the 1964, May 8 record is reproduced with a 5-time magnification, and the 1964, May 12 record is also shown for comparison (Kawasaki, K. and Akasofu, S.-I.: Planet. Sci. 20, 1163, 1972; Akasofu, S.-I. D., Reidel Publishing Co., 1977).

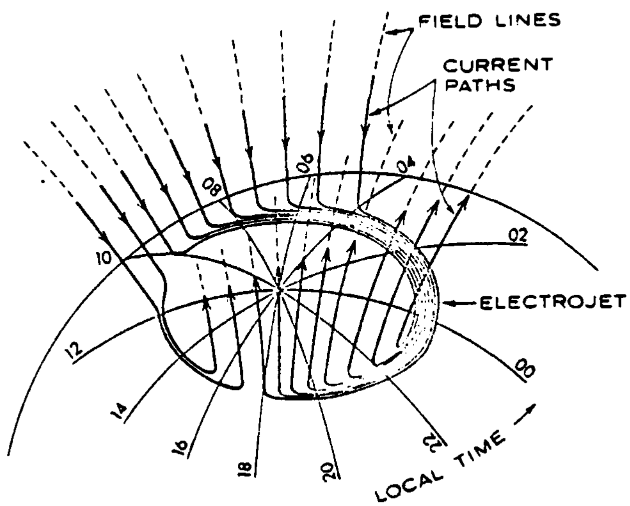

Figure 20. Schematic representation of S_q^p current (Knecht, 1972).

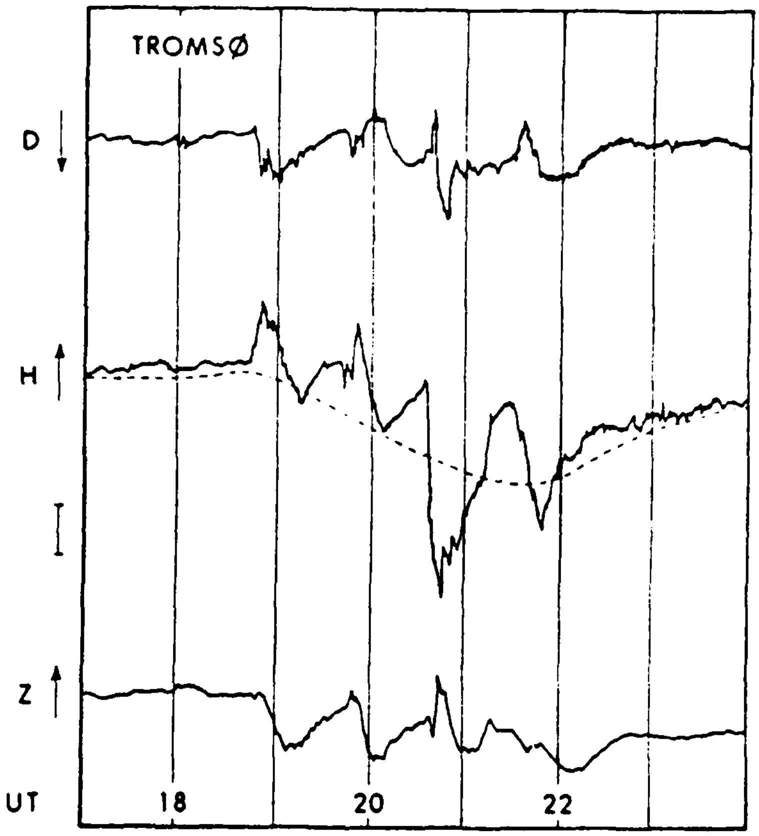

Figure 21. Magnetogram from Scandanavian station of Tromsφ (66^{o}N) showing polar magnetic substorms superposed on long-period geomagnetic bay disturbance. The substorm is best described by a single-cell equivalent-current system, whereas the long-period bay is best described by the two-cell system (Rostoker in Zmuda, 1974).

pronounced in the H component record. Positive bays (+ΔH) are associated with the eastward current and negative bays with the westward current in the morning sector. The term magnetic bay can prove confusing as it has been applied to both this signal as well as magnetic substorm signals. While they are often related there is a difference that is also evidenced in Figure 21.

It has also been noted that certain fluctuations occur in polar and equatorial recordings in phase (Figure 22). A polar current that is broad in extent (Figure 23) has been developed to model these fluctuations. The current system has been called the DP2 current (with DP1 being ascribed to the electrojet).

It must be noted that there is no universal agreement as to the source or nomenclature of such auroral/polar disturbances. Indeed the opposite is quite true. We have some authors equating S_q^p to DP2 and others presenting more planar current systems as opposed to the electrojet type. What can be said is that the auroral/polar region is the most complex area of external geomagnetic phenomena which is just being unraveled.

Polar Cap Disturbances

Actually there is quite a distinction between the actual polar cap region and the auroral region although too often we use the term polar to describe the general area of geomagnetic phenomena when it should be considered as only a geographical indicator. However in terms of geomagnetic phenomena the polar cap region is that area above about 80° geomagnetic latitude. This region is not as disturbed nor as dynamic as the auroral zone but it is quite nebulous due in part to the paucity of observatories in the area. Basically in terms of geomagnetic phenomena the region above the auroral oval to approximately 80° geomagnetic latitude is a transitional zone that shows some auroral type phenomena and some polar cap phenomena. In the polar cap region itself the magnetic activity is anticorrelated with the features in the auroral zone. In general, two major types of disturbances are observed; those coincident with bay disturbances in the auroral zone and a disturbance which occurs in the sunward

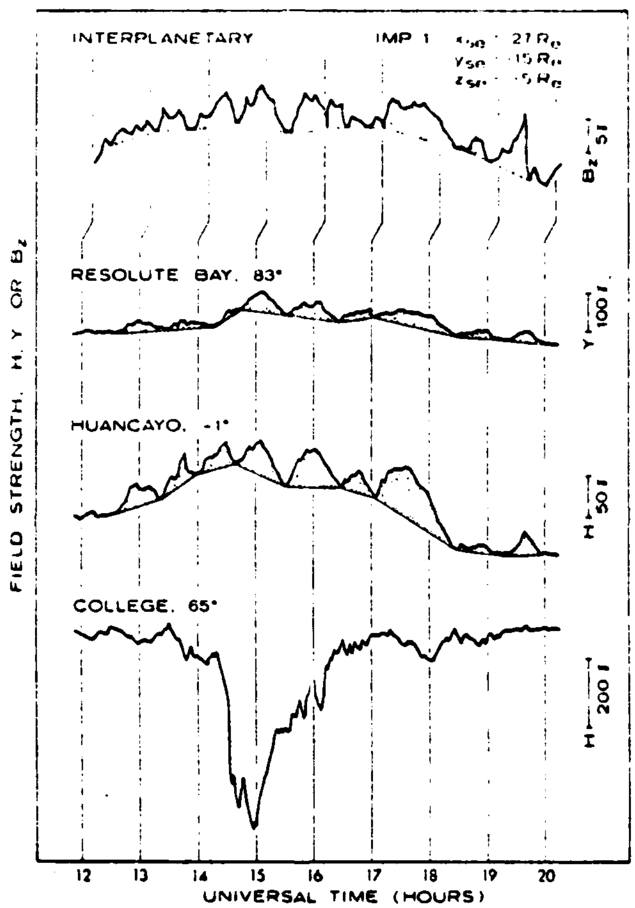

Figure 22. Example of DP2 magnetic disturbance, as shown in polar, equatorial, and auroral-zone magnetograms (2nd, 3rd, and 4th traces, respectively). The DP2 component is shaded where distinguishable. The first trace shows the southward (z_{se}) component of the interplanetary field, plotted with a time lag of 10 minutes [redrawn after Nishida, 1968], (Knecht, 1972).

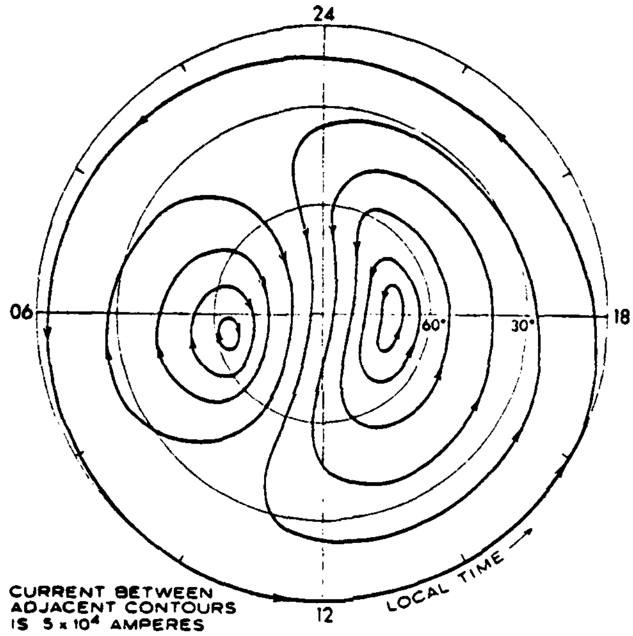

Figure 23. The equivalent current system derived for DP2 magnetic disturbance [redrawn after Nishida, 1968; Knecht, 1972].

or daylight area (except winter) centered near local noon. The disturbances associated with auroral bays are undoubtedly the result of some ionospheric current (perhaps a return current across the polar cap) although the exact current configuration is unknown. The disturbance near local noon is not completely understood but is observed in daytime magnetograms when the general level of magnetic field activity is quite low. This area has been termed the region of high latitude field agitation or the area of confusion.

There has been noted in the study of magnetic storms a remarkable correlation with the direction of the interplanetary magnetic field (IMF), particularly when the field is directed toward the south (Bz). Studies of polar cap phenomena have also shown that disturbances observed in this region are related to the direction of the IMF. Figure 24 shows the equivalent current vectors in the polar cap region for northward and southward directed IMF fields. The difference is remarkable and the resultant magnetic field effects quite understandable. Additional studies have also shown that variations termed DPC variations observed in the polar cap region are related to the IMF by component.

Low Latitude Disturbances

The only disturbed variations in the mid and low latitude regions are effects of solar flares and a subtle effect due to the direction of the IMF. During violent solar flares the emission of energy in the x-ray region is greatly enhanced. The resultant x-ray emission causes an increase in ionization and hence conductivty in the lower levels of the ionosphere. This conductivity increase occurs in the D region of the ionosphere (the Sq current system occurs in the higher E region) where the wind system is different. Consequently the solar flare does not simply enhance the Sq current system but rather results in the formation of an additional current system in the lower ionosphere. This current system is shown in Figure 25 and the observed variation is called a solar flare effect or crochet. There is also an augmentation of the equatorial electrojet effect as a result of the increased conductivity and an effect in the polar cap region termed polar cap absorption.

The IMF affects the Sq current system in the fact that the focus is about 4° further north when IMF is directed toward the earth than when it is directed toward the sun.

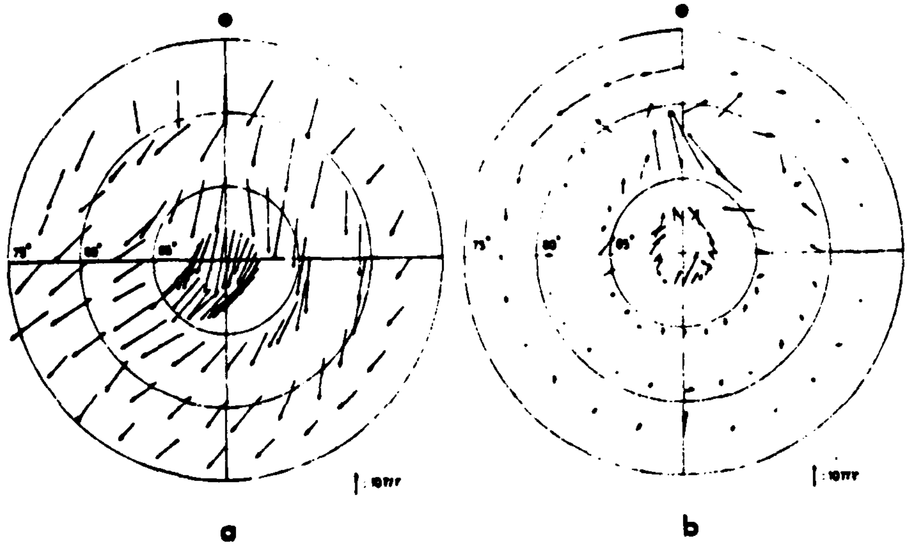

Figure 24. Equivalent current vectors with arrow directions reversed to indicate the direction of cross polar cap convective flow as computed by Maezawa (1976). Part (a) pertains to southward IMF and part (b) to northward IMF. The scale factor at the bottom of each figure relates polar cap magnetic field perturbation strength to north-south IMF (the ratio being 10: 1). Note the remarkable reversal of convective flow from (a) to (b) in the dayside cleft region (Rostoker, 1978).

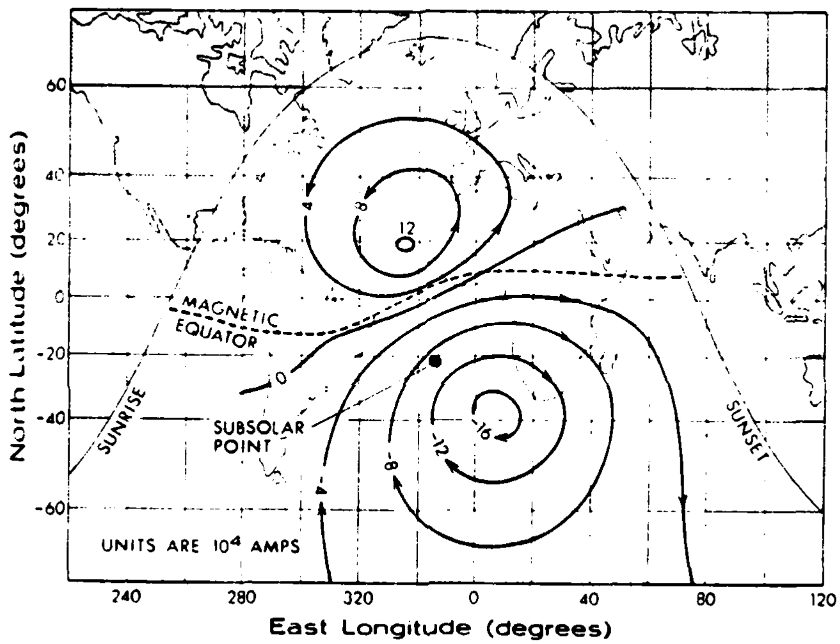

Figure 25. The ionospheric current system of a solar-flare effect occurring near winter solstice (12th December 1958). For an SFE on 29th July 1958, the northern vortex was much more intense than the southern [redrawn after van Sabben, 1961; from Knecht, 1972].

Additional Disturbances

The remaining melange of disturbed variations such as sudden impulses due to solar wind pressure changes and micropulsations are not of particular importance to magnetic survey problems owing to their scarcity, spectral frequency, or low amplitude level and thus are not discussed in this report.

MAGNETIC ACTIVITY INDICES

For purposes of correcting magnetic survey data it is desirable to know the state of the external field. While the general degree of activity can be monitored by a recording base station magnetometer, or by analysis of available magnetograms, it is often necessary to have a quantitative indicator as an aid in evaluating external field conditions. Over the past few decades many such indicators, termed magnetic activity indices, have been developed basically for correlative studies of geomagnetic phenomena. While some of these can have utility to the objectives of correcting magnetic survey data, the majority are not of particular value and indeed most of the lesser indices are of historic rather than practical importance even to geomagnetic studies. The most relevant to our topic are the Kp, Ap, AE, and Dst indices both from the standpoint of indicators of fairly distinct aspects of the external field and their availability in digital form in a timely manner. However, for completeness, the other indices, as listed in Table 1, will also be briefly summarized. Excellent reviews of all geomagnetic indices including information on availability are contained in Lincoln (1967), Rostoker (1972), and Knecht (1972).

Planetary Indices K and A

These indices were developed to represent the general state of geomagnetic activity. The indices are derived from selected observatories at mid latitude locations (to minimize contributions from the electrojets) and have served as standards for several decades. However the Planetary Indices, as is the case of all the indices, suffer from the lack of an adequate distribution of observatories and the fact that the external fields are so highly irregular. For example in some cases auroral substorms may not effect the magnetograms at the selected observatories whereas in other cases, perhaps due to the equatorial migration of the auroral electrojet, they may significantly do so. In fact these indices represent mixture of disturbance effects associated with many of the external fields and have proven useful for very general correlations of geomagnetic phenomena.

TABLE 1

SUMMARY OF MAGNETIC ACTIVITY INDICES

Index	Range	Comments
	Planetary Indices K and A	
K Ks	0 - 9 0.0 - 9.0 $0_o - 9_o$	- originally designed as a measure of solar wind influence - fairly well suited as indicator of general magnetic activity - three hour indices on a quasi-logarithmic scale based on a measure of the irregular variations on standard magnetograms - Kp is the average from selected mid latitude observatories whose K indices are translated into standard indices (Ks)
aK	0 - 400	- transformation of K indices to a linear scale
Ak	variable	- daily average of aK's
ap	0 - 400	- transformation of Kp indices to a linear scale
Ap	variable	- daily average of ap's
	Auroral Electrojet and Ring Current Indices	
Ae	variable	- maximum difference on composite magnetogram obtained from 2.5 minute samples at 10 sub auroral zone observatories - qualitative measure of auroral electrojet intensity
Dst	Several tens of gammas positive to several hundreds of gammas negative	- quantitative meausre of field due to ring current - symmetric part of disturbance field from 4 mid to low latitude observatories

TABLE 1 (Cont'd)

Index	Range	Comments
		Indices of Historical Importance
Q	0 - 11	- 15 minute index - uses horizontal components only, therefore sensitive to ionospheric currents - polar observatories above 58 degrees latitude
R	variable	- similar to Q but an hourly measure - polar observatories above 65^{o} latitude
C	0 - 2	- daily character index for each observatory - quite subjective
Ci	0.0 - 2.0	- daily world wide index, average of all C indices
Cp	0.0 - 2.5	- daily activity index similar to Ap, a conversion of kp indices
C9	0 - 9	- contraction of Ci or Cp for graphical display purposes
U	variable	- type of ring current measure - only suitable for monthly or annual mean studies
W	variable	- computed at Huancayo observatory - designed to measure solar radiation effects and as an index of the intensity of the equatorial electrojet
		New Indices
kn	0 - 9	- new index replacing kp, north component
ks	0 - 9	- new index replacing kp, south component
km	0 - 9	- new average index replacing kp
aa	variable	- new index replacing Ak - converts k index to amplitude in gammas

K, Ks, Kp

The Kp index is undoubtedly one of the more generally used of all magnetic activity indices. Routinely published in the Journal of Geophysical Research, it is also available through the world data centers and publications of the International Association of Geomagnetism and Aeronomy.

It was first introduced by Bartels (1949) and Bartels and Veldkamp (1949) and intended to be a measure of solar corpuscular radiation based upon the intensity of geomagnetic activity resultant from the solar wind. It is now utilized as a general indicator of worldwide magnetic activity.

The first step in deriving the Kp index is the determination of K indices for the selected midlatitude observatories. This is accomplished by measuring the maximum range of the most disturbed component (excluding the vertical because of induction effects) over a three hour interval after the regular daily variations have been removed. This range, measured in gammas, is then translated into the nondimensional K index through standardized tables.

The standard observatory, selected in 1938, was Niemegk, and a table developed equating the quasi-logarithmic K index (ranging from 0 to 9) to the measured disturbance range. A frequency analysis of the other selected observatories was utilized (ensuring the same number of K's = 1, 2 etc.) to produce conversion tables for the other observatories. Thus the K indices represent the level of magnetic activity at these separate observatories. In order to intercompare such indices it is necessary to remove the effects of regional conditions at the individual observatories. Such regional effects could be due to conductivity differences, localized or proximate geomagnetic activity, and also seasonal and local time differences. Thus a standardization process was developed to convert K into the K's or standardized K index which is a continuous variable ranging between 0.0 and 9.0 and given in thirds of an integer, i.e., 1.5 to 2.5 becomes 2^-, 2_o, 2^+ and the range is from (0_o to 9_o).

Kp or the planetary magnetic activity index is a simple average of the K's indices and ranges from 0_o to 9_o.

aK, Ak, ap, Ap

The Kp indices are of limited value in mathematical analysis because of their quasi-logarithmic scale. Although a $\sum Kp$ index is computed it should be used with caution as a daily activity indicator because of the misleading results that can occur in the addition of quasi-logarithmic quantities (Bartels, 1957). To overcome such difficulties Bartels (1951) introduced the daily equivalent planetary amplitude Ap which is an average of eight ap indices which in turn are computed from the Kp indices. As Rostoker (1972) points out the origin of the ap scale, and conversion from Kp index, is somewhat obscure and the reasons for the choice of 400 as highest value has not been documented. Standard tables have been developed for the calculation of ap from Kp indices and are routinely employed. Basically the ap index can be utilized to determine the magnitude of the most disturbed component at a standard midlatitude station as the ap index is in units of 2γ.

A parallel set of indices for the individual stations are the Ak and ak indices. With Ak being the daily average of the eight ak indices which are computed from the K indices.

Auroral Electrojet and Ring Current Indices

As previously mentioned the planetary magnetic activity indices are influenced by contributions from many external field sources. For certain investigations, and indeed for the purposes of correcting magnetic survey data, it is desirable to have indices indicative of the contribution of particular current systems. Two such indices are the AE and Dst indices.

AE

Davis and Sugiura (1966) proposed the AE index as an indicator of the auroral electrojet contribution to auroral zone activity. The index is computed using data from selected sub auroral zone observatories that are well distributed in longitude. Valves of the disturbed H component are selected at 2.5 minute intervals from each observatory and superimposed to form a composite magnetogram. The envelope of the valves is utilized in the derivation of the index. The amplitude of the upper portion of the envelope is termed AU and represents the maximum perturbation caused by the eastward electrojet. The lower portion of the envelope, termed AL, represents the effect of the westward electrojet. AE is the difference, at 2.5 minute intervals, between these two (i.e., AU-AL) measured in gammas. Another aspect of the curves, though little used is the mean deviation, termed Ao, defined by the curve midway between AU and AL.

Dst

Sugiura (1964) developed the Dst index as an indicator of the strength of the ring current alone. Dst is the term used for the symmetric part of the disturbance field, i.e., the departure from the normal daily variations recorded on observatory magnetograms. As noted earlier in this text the ring current is located at several earth radii and and resultant field observed on the earth is fairly uniform over the globe. Sugiura uses H component data from four low to midlatitude observatories that are well distributed in longitude. After removing effects of regular variations and correcting for base levels, Sugiura averages the resultant data from the observatories to obtain the Dst index. The index is in gammas and ranges from several tens of gammas positive to several hundreds of gammas negative. The index represents the strength of the ring current field at the geomagnetic equator.

Indices of Historical Importance

There are many magnetic activity indices that are now used to a lesser degree that should be discussed for the sake of completeness.

Q

The Q index was an index computed for 15 minute intervals at polar observatories, i.e., above 58° geomagnetic latitude during the International Geophysical year. The index was developed to serve as a short period index for correlation with many other geophysical measurements made at similar intervals.

The Q index is computed in a manner similar to the K index in that the maximum amplitude of the most disturbed horizontal component is measured. However a uniform scale is used to convert the upper limit of the amplitude variation to the Q index which ranges from 0 to 11.

R

The R index is an hourly index computed by polar observatories at geomagnetic latitudes greater than 65 degrees. The index is the absolute hourly range in tens of gammas for each horizontal component.

C, Ci, Cp, C9

C is the daily character figure for a single observatory derived from a qualitative inspection of an entire magnetogram. It has the values of 0, 1, 2; with 0, being very quiet; 1, moderately disturbed; and 2, severely disturbed. It has been found to be, understandably, a very subjective index.

Ci is the daily international character figure which is an arithmetic mean of the C indices and ranges from 0.0 to 2.0.

Cp is analagous to Ci in that the day's ap indices are summed and converted to the Cp index (range 0.0 to 2.5) by a table (Lincoln, 1967, p. 75) developed from years of observations.

C9 is a single digit representation of either Ci or Cp, again computed by means of a standard table (Lincoln, 1967, p. 75).

U, U_1

The U measure is an old type of ring current indicator derived from measuring the difference of the mean valve of horizontal intensity of one day from the value of the preceeding day and correcting for direction of the geomagnetic field and latitude. The measure is not utilized today, U_1 is a corrected form of U by removing any magnetic storm effects.

W

This index (or measure) is based upon the amplitude of the Sq variations in the horizontal component at the Huancayo Peru Magnetic Observatory. Because of the observatory's location the index is intended to be an indicator of the intensity of the equatorial electrojet and ultimately a measure of solar radiation effects.

New Indices

Over the past few years several new indices have been developed (e.g., Mayard, 1975; Svalgaard, 1976) in attempts to overcome many of the shortcomings of the established indices or for purposes of particular geomagnetic phenomena. As these are still quite new and not as yet established, nor readily available, they are not covered in this text but only noted in Table 1.

SUMMARY

THE PROBLEM OF EXTERNAL FIELD CORRECTIONS IN MAGNETIC

As was noted in the introduction there is considerable interest in the removal of external field effects from magnetic surveys. Although repeated base station observations can be utilized to accomplish this in very local land-based surveys, such a method is not valid for large scale surveys and impractical in oceanic and airborne operations. While tie lines are employed in these latter cases, the practical problems of positional accuracy and repeatability can produce considerable source of error. It has also been common practice in recent years to deploy a stationary magnetometer in the region of airborne (and shipborne) operations to be used as a reference value for the removal of external temporal variations. However such a technique is suspect as the coherency of the external field signal and the effects of conductivity differences (affecting the induced component) over the survey area are not known. The problem is further complicated in shipborne operations in that it is often difficult to obtain a stationary platform for the recording magnetometer. While gradiometers have been employed in both types of surveys the problems of maintaining relative and absolute position of the sensors as well as adequate sensor spacing has proven to be a problem. Thus the problem of external field correction in magnetic surveys is still at hand and warrants further examination.

While a complete solution to this problem can not be given at this time we can outline a rationale for dealing with the external field problem and indicate steps to be taken in working toward such a solution. First of all, as was noted earlier, we must begin with an understanding of the effects that we are trying to correct for. Secondly, the practical problem of designing surveys to minimize the external field effects or monitoring and removing external fields must be considered. In this manuscript we have addressed the first item by attempting to provide some insight into the phenomena of external fields. The subject is quite complex and in summary it is helpful to review these fields and consider how this material relates to the problem of removing their effects from magnetic surveys.

First of all there are very definite regions of the globe over which the external field effects are quite different which should be considered in planning survey operations. These are shown schematically in Figure 26. The regions as noted in this report are the equatorial, mid latitude, auroral, and polar cap zones. They are functions of geomagnetic latitude and the geomagnetic coordinate system must be considered in the analysis or representation of external field phenomena. For often external field effects appear highly irregular and uncorrelated when viewed from a geographic point of view. Order is brought to apparent chaos only through use of the geomagnetic coordinate system.

Secondly the intensity, duration, and various parameters of the external fields must be considered. These are summarized in Table 2. In considering the influence of external fields on magnetic surveys the particular fields active at the time of the survey should be noted. As we have noted not all external fields are active at the same time. First of all the area to be surveyed should be noted and the external fields likely to be a factor determined. Then additional parameters such as solar cycle, magnetic activity, indices, season, universal and local time noted to determine the relevance of the anticipated external fields. In such a manner some insight can be gained into what external fields may be encountered and their effects minimized, or avoided.

To make such an approach more quantitative it would be useful to have charts showing the anticipated effect of each type external source on a global basis as a function of their relevant parameters. Such charts could be generated utilizing the various models of external field sources (e.g., Sugiura and Hagan, 1967; Olson, 1980). In support of such charts it would also be helpful to develop key magnetic activity indices which would indicate the relative state of activity or influence of the various sources.

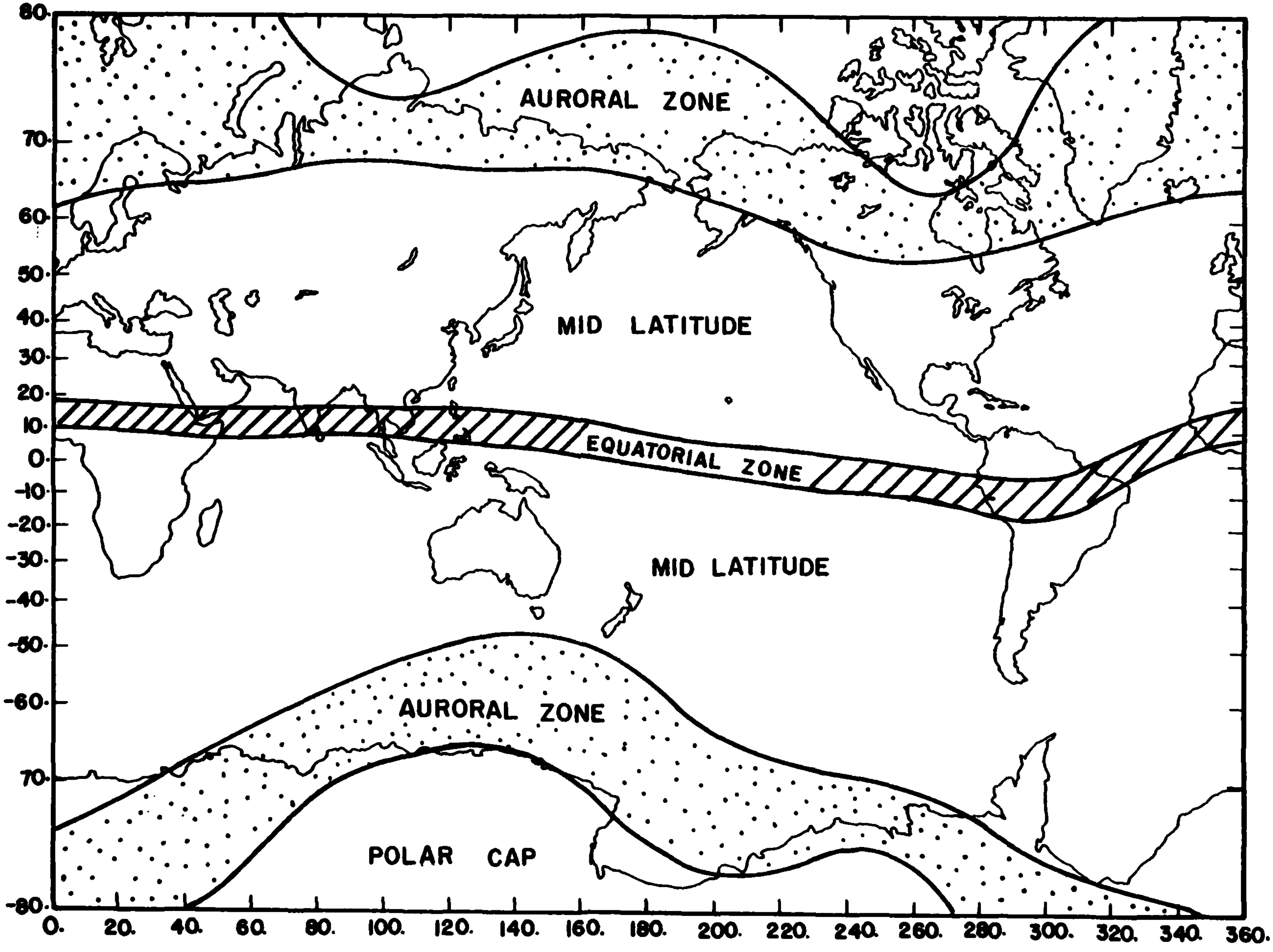

Figure 26. Regions of Various Observed External Field Effects

TABLE 2

GENERAL CHARACTERISTICS OF EXTERNAL MAGNETIC FIELD TEMPORAL VARIATIONS

Type	Origin	Typical Amplitude* (Gamma)	Typical Period*	Comments
		Quiet Variations		
Sq	Solar electromagnetic radiation and gravitational influence on ionosphere	tens	several hours	- main variations during day - correlated with local time - abnormally high near dip equator (equatorial electrojet) - greater in summer than in winter - subtle variation with IMF direction
L	Lunar tidal influence on ionosphere	several	several hours	- main variations during day - varies with lunar phase and season - abnormally large over dip equator-greater magnification than Sq
		Disturbed Variations		
Magnetic Storm	Interaction of solar plasma with magnetosphere	several hundred	several days	
- initial phase	Magnetospheric compression		hours	- abrupt increase in magnetic field - highly irregular
- main phase	- enhanced ring current - combined effects of magnetospheric substorms-release of energy from tail		1 - 2 days	- gradual decrease below pre-storm level
- recovery phase	- decay of ring current		hours - days	- gradual return to pre-storm level

TABLE 2 (Cont'd)

Type	Origin	Typical Amplitude* (Gamma)	Typical Period*	Comments
Magnetic bays	- auroral electrojet (DP1) - magnetospheric substorms	hundreds	several hours	- mostly an auroral zone phenomena - effect can extend over 100° in longitude from source - intensity of onset depends on proximity to source - maximum intensity near geomagnetic midnight
S	- polar ionospheric current	tens	several hours	- auroral zone phenomena analagous to Sq
DP2	- polar ionospheric current	several	minutes	- global phenomena
Zone of high latitude field agitation	?			- occurs in polar cap area near local noon (except winter)
DPC	- IMF By			- polar cap phenomena
Crochet (solar flare effect)	- enhancement of ionization by solar flare x-ray . emission			- apparent sudden amplification of Sq - increase in equation electrojet effect
Micropulsations				
- pc	- ionospheric magnetospheric perturbations	several	2 - 40 sec.	- classified into subgroups - diurnal - maximum near local noon
- pt	- related to polar disturbances	several	2 min - 1 hour	- nocturnal - related to magnetic bay
- pp	- hydromagnetic emissions	several	0.2 - 5 sec.	- amplitude modulated

*Amplitudes and periods of external magnetic field temporal variations are highly variable and depend on their physical origin as well as the geomagnetic latitude, longitude, and time of the observation point. Values given here are typical.

As previously noted, in addressing the practical problem of correcting for external fields, one of the most attractive techniques, and one that has been employed over the past few years (although it must be mentioned with little regard to the complexity of the problem), is to deploy a stable temporal monitor (magnetometer) in the vicinity of the survey and suitably adjust survey data for the variations observed on the monitored record. However, there are many pertinent theoretical and operational questions that must be answered before the utility of such an approach can be accurately assessed. They include the determination of the coherency of the various external field signals, effect of typical terrestrial conductivity distributions, and the optimal way in such a technique can be employed, including the number and distribution of deployed monitors. Some steps in addressing these problems are outlined below.

With the advent of the International Magnetospheric Study (IMS) an investigation into the coherency of the sources is now possible. The IMS magnetometer network (Lanzerotti, et al, 1976) spans a significant portion of the North American continent and offers a unique opportunity to study the coherency of the external source fields. Utilizing data from selected stations in this array and correlating with conventional magnetic observatory measurements (many of the IMS stations do no have calibrated baselines) the spatial coherency of the various components of the external field could be adequately detailed.

Then the effect of electrical conductivity distribution must be determined. When comparing temporal variations between various temporal monitors (such as magnetic observatories) the effects of local conductivity structure often cause sizable differences in magnetic measurements between monitors. Classic examples of such differences are at magnetic observatories in Japan (Rikitake et al, 1966) and Germany (Schmucker, 1959) where the behavior of the vertical ΔZ and horizontal ΔH was observed to vary greatly over short distances. These geomagnetic variation anomalies are believed to be due to conductivity anomalies and the induced currents associated with them.

To approach this problem, the following could be done. First, identify large scale anomalous regions and their characteristic transient field behavior (from the literature), then model 2- and simple 3-dimensional conductivity structures to study the degree of their effect on the magnetic field. Finally for the simple models explored, examine how many monitors and how location dependent they are in order to map the anomalous effect.

Work must then be done to translate such theoretical studies into the practical realm by designing optimal deployment schemes for ground based monitoring systems in a survey area. Apriori it would appear that a tripartite type array would be best suited with the locations of the monitors dependent upon knowledge of the conductivity distribution and the design of the survey. Initially various types of deployment schemes could be tested with a computer model and finally, if possible, actual test cases conducted.

Thus, although much work is still to be accomplished in adequately addressing this problem a significant start has been made through research programs sponsored by the Office of Naval Research and the Naval Oceanographic Office. Hopefully within several years time the removal of external field effects from magnetic survey data will be a routine matter.

REFERENCES

Akasofu, S., 1977, Physics of magnetospheric substorms, D. Reidel Publishing Co.

Akasofu, S., 1968, Polar and magnetospheric substorms, Springer Verlay.

Armstrong, J.C. and Zmuda, A.J., 1970, Field aligned current at 1100 km in the auroral region measured by satellite, J. Geophy. Res., v. 75, p. 7122.

Axford, W.I. and Hines, C.O., 1961, A unifying theory of high latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., v. 39, p. 1433.

Bartels, J., 1949, The standardized index, Ks, and the planetary index, Kp, Int. Union Geod. Geophy. IATME Bulletin, No. 12b, p. 97.

Bartels, J., 1951, Inter. Union Geod. Geophys. IATME Bulletin, No. 12e, p. 109.

Bartels, J., 1957, The geomagnetic measures for the time variations of solar corpuscular radiation described for use in correlation studies in other geophysical fields, Ann. Int. Geophy. Year, No. 4, Part 4, p. 127.

Bartels, J., and J. Veld Kamp, 1949, Geomagnetic and solar data, J. Geophys. Res., v. 54, p. 295.

Bleil, D.F., 1964, Natural electromagnetic phenomena below 30 kcls, Plenum Press.

Bostrom, R., 1964, A model of the auroral electrojets, J. Geophys. Res., v. 69, p. 4983.

Carlson, C.W. and Kelley, M.C., 1977, Observation and interpretation of particle and electric field measurements inside and adjacent to an active auroral are, J. Geophys. Res., v. 82, p. 2349.

Carpenter, L.A. and Kirchhoff, V.W.J.H., 1975, Comparison of high-latitude and mid-latitude ionospheric electric fields, J. Geophys. Res., v. 80, p. 1810.

Cain, J.C. and Sweeney, R.E., 1973, The POGO data, Jour. of Atmo. and Terr. Physics, v. 35, p. 1231.

Chapman, S. and Bartels, J., 1940, Geomagnetism, Oxford University Press.

Cummings, W.D., 1966, Asymmetric ring currents and the low latitude disturbance daily variation, J. Geophys. Res., v. 71, p. 4495.

Davis, T.N., and Sugiura, M., 1966, Auroral electrojet activity index AE and its universal time variations, J. Geophys. Res., v. 71, p. 785.

Fambitakoye, O. and Mayaud, P.N., 1976, Equatorial electrojet and regular daily variation S_R, I, A determination of the equatorial electrojet parameters, J. Atmos. Terr. Physc., v. 38, p. 1.

Feldstein, Y.I., Magnetic field variations in the polar region during magnetically quiet periods and interplanetary magnetic fields, Space Sci. Rev., v. 18, p. 777.

Fukushima, N., 1975a, Equivalent current pattern for a field-aligned current into into the auroral belt of enhanced electric conductivity, Part II, Case of charge accumulation at the auroral-zone boundaries, Rep. Ionos. Space Res. Japan, v. 29, p. 31.

Fukushima, N., 1975b, Equivalent current pattern for a field-aligned current into the auroral belt of enhanced electric conductivity, Part III. Case of open field lines of the poleward side and closed field lines of the equatorward side of the auroral belt, Rep. Ionos. Space Res. Japan, v. 29, p. 39.

Fukushima, N., 1975c, Electric current system over the polar cap region with or without magnetic effect on the ground, Rep. Ionos, Space Res. Japan, v. 29, p. 47.

Gurevich, A.V., Krylov, A.L., and Tsedilina, E.E., 1976, Electric fields in the earth's magnetosphere and ionosphere, Space Sci. Rev., v. 19, p. 59.

Heikkila, W.J., 1973, Aurora, EOS, Trans. AGU, v. 54, p. 764.

Heppner, J.P., 1977, Empirical models of high-latitude electric fields, J. Geophys. Res., v. 82, p. 1115.

Hughes, T.J. and Rostoker, G., 1977a, Current flow in the magnetosphere and ionosphere during periods of moderate activity, J. Geophys. Res., v. 82, p. 2271.

Hughes, T.J. and Rostoker, G., 1977b, A model three-dimensional current system for steady state conditions in the magnetosphere, J. Geophys. Res., in preparation.

Kamide, Y. and Akasofu, S.-I., 1975, The auroral electrojet and global auroral features, J. Geophys. Res., v. 84, p. 3585.

Kamide, Y. and Akasofu, S.-I., 1976a, The auroral electrojet and field-aligned current, Planet. Space Sci., v. 24, p. 203.

Kawasaki, K. and Akasofu, S.-I., 1973, A possible current system associated with the S_q^p variation, Planet. Space Sci., v. 21, p. 329.

Knecht, D.J., 1972, The geomagnetic field (a revision of Chapter 11, Handbook of Geophysics and Space Environments) Air Force, Cambridge Research Lab., Air Force, Surveys in Geophysics, No. 246.

REFERENCES (cont'd)

Langel, R.A., 1975, Near earth magnetic disturbances in total field at high latitudes 2, interpretation of data from OGO 2,4, and 6, Jour. of Geophys. Res., v. 79, p. 2373.

Lanzerotti, L.J., Regan, R.D., Sugiura, M., and Williams, D.J., 1976, Magnetometer networks during the international magnetospheric study, EOS, v. 57, no. 6, p. 442.

Lincoln, J.V., 1967, Geomagnetic indices, in physics of geomagnetic phenomena, v. 1, edited by S. Matsushita and W.H. Campbell, pp. 67-100, Academic Press, New York.

Matsushita, S., 1968, Polar daily geomagnetic disturbances, Ann. Geophys., v. 24, p. 227.

Matsushita, S., 1969, Dynamo currents, winds, and electric fields, Radio Science, v. 4, no. 9, p. 771.

Matsushita, S. and Maeda, H., 1965a, On the geomagnetic solar quiet daily variation field during the IGY, Jour. Geophy. Res., v. 70, p. 2535.

Matsushita, S. and Maeda, H., 1965b, On the geomagnetic lunar daily variation field, Jour. Geophys. Res., v. 70, p. 2559.

Matsushita, S. and Campbell, W.H., 1967, Physics of geomagnetic phenomena, Academic Press, New York, (2 vol.)

Mayaud, P.N., 1975, Analysis d'une series centenaire d'indices d'activite magnetique, I. Rechorche d'un effet lunaire et recurrence de 27 jours, Ann. Geophys., v. 31, p. 419.

Mayaud, P.N., 1976, Magnetospheric and nighttime induced effects in the regular daily variation S_R, Planet. Space Sci., v. 24, p. 1049.

Oldenburg, D.W., 1976, Ionospheric current structure as determined from ground-based magnetometer data, Geophys. J., v. 46, p. 41.

Olson, W.P., 1970, Contribution of nonionospheric currents to the quiet daily magnetic variations at the earth's surface, J. Geophys. Res., v. 75, p. 7244.

Olson, W.P., 1972, Distributed magnetospheric currents and their magnetic effects (abs), EOS, Trans. AGU, v. 53, p. 1089.

Olson, W.P. (ed), 1980, Quantitative modeling of magnetospheric processes, American Geophysical Union.

Regan, R.D. and Cain, J.C., 1975, The use of geomagnetic field models in magnetic surveys, Geophysics, v. 40, no. 4, p. 621.

Rishbeth, H. and Garriott, O.K., 1964, Introduction to the ionosphere and geomagnetism, Stanford Electronics Laboratory.

Rikitake, T., 1964, Outline of the anomaly of geomagnetic variations in Japan, J. Geomagnetism Geoelectec, 15, p. 181-184.

Rikitake, T., 1966, Electromagnetism and the earth's interior, Elsevier, Amsterdam.

Rostoker, G., 1972, Geomagnetic indices, Rev. Geoph. and Space Phys., v. 10, p. 935.

Rostoker, G., 1978, Electric and magnetic fields in the ionosphere and magnetosphere, Jour. of Geomag. and Geoelect., v. 30, p. 67.

Rostoker, G., Armstrong, J.C., and Zmuda, A.J., 1975, Field-aligned current flow associated with the intrusion of the substorm intensified westward electrojet into the evening sector, J. Geophys. Res., v. 80, p. 3571.

Schmucker, U., Erdmagnetische tiefensondierung in deutschland 1957-1959, Magnetogramme und erste auswertung, Abhandl. Akad. Guttingen, Math. Physik, Kl., Beitr. 1.G.J. 5: 1-51.

Sugiura, M., 1964, Hourly values of equatorial Dst for the IGY, Ann. Int. Geophy. Year, v. 35, p. 9.

Sugiura, M., 1972, The ring current, in critical problems of magnetospheric physics, edited by E.R. Dyer, IUCSTP Secretariat, National Academy of Sciences, Washington, D.C., p. 195.

Sugiura, M., 1973, Quiet time magnetospheric field depression at 2.3 to 3.6 R_E, Jour. Geophys. Res., v. 78, p. 3182.

Sugiura, M., 1975, Identification of the polar cap boundary and the auroral belt in the high latitude magnetosphere: A model for field-aligned currents, J. Geophys. Res., v. 80, p. 2057.

Sugiura, M., 1976, Field-aligned currents observed by the OGO 5 and triad satellites, Ann. Geophys., v. 32, p. 267.

Sugiura, M. and Hagan, M.P., 1967, Universal-time changes in the geomagnetic solar quiet daily variation Sq, Scientific Report for NSF, GA-478.

Sugiura, M., and Heppner, J.P., 1968, The earth's magnetic field, in introduction to Space Science, Second Edition, edited by W.N. Hess and G.D. Mead, Gordan and Breach, New York.

Svalgaard, L., 1976, Recalibration of Bartel's geomagnetic activity indices Kp ap to include universal time variations, J. Geophys. Res., v. 81, p. 5182.

Zmuda, A., 1974, The geomagnetic field of external origin as observed at the earth's surface, EOS, Trans. of Amer. Geophys. Union, v. 55, no. 6, p. 588.

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This report sponsored by the Earth Physics Program of the Office of Naval Research, is an attempt to bring together in a coherent manner, for those involved in magnetic surveys, the relevant aspects of the external geomagnetic field. Although there are several excellent introductory texts on geomagnetism that treat much of this subject (most notably, Sugiura and Heppner, 1968; and Knecht, 1972) it was thought that there was a need to condense and present this and other supportive material in a form that would be more applicable to the objectives of magnetic surveys, as there is considerable interest in correcting

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) magnetic surveys for the effects of the external field. Such efforts must start with a sufficiently detailed understanding of the geomagnetic environment in which magnetic survey data are collected and particularly of the various external field sources. Hopefully this report will serve to provide such an understanding.